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TECHNIQUES USED TO MEASURE THE HYDRAULIC CHARACTERISTICS OF THE NASA PLUM BROOK REACTOR

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TECHNIQUES USED TO MEASURE THE HYDRAULIC CHARACTERISTICS OF THE NASA PLUM BROOK REACTOR[1]

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I - SUMMARY OF CORE TESTING EXPERIMENTS

SUMMARY

The basic objectives of the hydraulic testing program for the NASA Plum Brook Reactor were to determine in detail the flow characteristics of the reactor core and reflector regions with instruments developed for this purpose and to correct any flow anomalies uncovered during the testing.

Built-in total-pressure and static-pressure probes were used to measure velocities in the cooling passages of the fuel assemblies, fuel section of the shim rod, and reflector components. Static-pressure distributions were also determined throughout the important regions of the active core. Special simulated fuel assemblies were developed and employed to measure the bulk flow rates through the inside of the assembly at each position of the core at steady state and during the transient period of coast down. Commercial pressure gages and inverted glass manometer tubes were used to measure pressure differences. Visual observations were made of the flow patterns in the large volume above the core.

Most of the tests were made at water temperatures in the range of 65° to 93° F and for the normal expected flow rates for full-power or shutdown reactor operations. The test results showed that flow and static-pressure distributions in the fuel and reflector regions of the core and the overall flow characteristics of the reactor were in close agreement with design specifications except for one flow anomaly. A flow starvation and some wide variations and fluctuations of the velocity and static pressure were found in the channels between the fuel assemblies and adjacent components, such as another assembly or a control rod. After much experimentation the causes of the flow anomaly were found. The flow resistance at the entrance to these passages was too high, and extraneous water was getting into the passages downstream from the entrance through holes in the control rods and other openings. A few additional factors that contributed to the problem are discussed.

To correct the flow anomaly, the sources of extraneous water were sealed or

[1]This is an expanded version of the report entitled "Methods of Testing the NASA Plum Brook Reactor for its Hydraulic Characteristics," presented at the conference on Light Water Moderated Research Reactors, sponsored by Oak Ridge National Laboratory, Oak Ridge, Tenn., June 11-14, 1962.

restricted, large elliptical holes were cut on each side of the upper fuel-assembly inlet diffuser, and the flow rate through the entire system was increased from the design value of 15,500 to 17,700 gallons per minute. These core modifications had no adverse influence on the flow characteristics of the core and reflector components. Thus, with these changes the hydraulics of the modified NASA Plum Brook Reactor satisfy all the flow requirements for full-power and shutdown operations.

All the instrumentation used in the core tests proved to be reliable, accurate, and relatively free of operational difficulties. The total- and static-pressure probes measured in detail the velocities inside the important cooling channels of the fuel assemblies and reflector components. A complete mapping of the static pressures in the core and other important locations was easily made with static-pressure probes and wall taps. The simulated fuel assemblies gave an accurate measure of the bulk flow distribution among the assemblies and of the rates during the flow coast down. The successful application of the techniques used in this reactor flow test suggests that they can be adapted to hydraulic tests of other reactors.

INTRODUCTION

The NASA Plum Brook Reactor (near Sandusky, Ohio) is a light-water-cooled and moderated reactor having a primary beryllium reflector and a secondary water reflector. The facility is described in detail in an unpublished NASA report, the "Final Hazards Summary, Plum Brook Reactor Facility," by A. B. Davis, B. Lubarsky, and T. M. Hallman, December 1959 (vols. 1 and 3). The core is a 3×9 array of plate-type fuel assemblies designed for a power output of 60 megawatts thermal at a maximum coolant temperature of 185° F and a pressure of 155 pounds per square inch absolute. Before the reactor can operate satisfactorily at maximum power, the coolant flow and pressure distributions in the core must be adequate. If any channel receives insufficient coolant, the wall temperature may rise above the maximum design limit. If the pressures are improperly distributed, a failure may occur; for example, a fuel plate may collapse. Hence, to prevent any damage to the reactor and possible serious accidents, any maldistributions of flow or pressures must be corrected or the operating power level must be reduced.

Usually it is very difficult to ascertain if a flow starvation exists and where it will occur by computational methods alone. This is because many reactor cooling channels have complex geometries whose flow characteristics cannot be accurately assessed. Consequently, the flow and static-pressure distributions in the reactor and reflector components must be determined by direct measurement before the reactor is started. Such a test program involves measurements within the core and many laboratory experiments.

A number of reports are available on the flow characteristics of various reactors located throughout the country. Also included are results on reactor components and some descriptions of the measuring techniques employed. In reference 1 static-pressure distributions were measured both inside and outside along the length of the fuel assemblies of the Materials Testing Reactor (MTR) in an effort to uncover the cause of certain fuel-assembly failures. The outer fuel plates were found to have an excessive pressure difference across the lower portion, which tended to buckle the plates outward. The causes of the excessive pressure difference were determined and the corrections made. Reference 2 describes the preneutron hydraulic tests performed on the Engineering Test Reactor (ETR) (water-cooled flat-plate fuel assemblies). Because the flows and pressure distributions were not in accord with the design, further tests were conducted on modified core components; the results are given in reference 3. In all the ETR tests velocity probes and static-pressure tubes were used to measure velocities in the cooling channels. Reference 4 gives the results of the hydraulic tests on the Oak Ridge Research Reactor (ORR) (water-cooled slightly curved plate fuel assemblies) in which an electrolytic method was used to measure water velocities. Even though the velocity data had considerable scatter, the flow distributions in the ORR were in substantial agreement with the design criteria. In reference 5 (pp. 15-19) the SPERT III Reactor (water-cooled flat-plate assemblies) hydraulic tests are very briefly discussed, and it was observed that spatial distribution of the coolant flow through the core and thermal shield regions was relatively insensitive to wide ranges in the flow, pressure, or system temperature. References 6 and 7 present studies of flow distribution through a quarter-scale model of the Pressurized Water Reactor (PWR) (water-cooled rod clusters). A very brief summary of the results of the tests conducted on the PWR is given in reference 8.

The purpose of this report is to describe the techniques employed to measure the hydraulic characteristics of the NASA Plum Brook Reactor and to summarize the test results.

REACTOR AND TESTING EQUIPMENT

Reactor, Reactor Tank, and Reactor Components

General arrangement. - A cutaway view of the NASA Plum Brook Reactor (PBR) showing the arrangement of the important equipment in and around the reactor tank is presented in figure I-1. Figure I-2 shows the general arrangement of all the components of the core and reflector regions. Figures I-2(a) and (b) are simplified somewhat to emphasize and identify the important coolant passages. Figure I-3 is a schematic plan view that gives the core and reflector region coordinate system and identifies clearly the positions of the fuel assemblies, control rod, and reflector pieces.

Fuel assemblies. - The PBR fuel assembly (fig. I-4) is a modified version of those used in the Materials Testing Reactor (MTR) at the National Reactor Testing Station, Arco, Idaho. The four recesses on the outer surfaces of the upper-end box are catches for the handling tools, and they also serve as inlets for the water flow around the outside of the assembly. The cutaway corners on the lower-end box provide an access to the semicylindrical outlets in the lower grid for this same water. As will be discussed later, the core test findings led to a modification of the upper-end box.

Core reflector components. - The beryllium reflector components in the core on the three sides of the active lattice are externally shaped very nearly like the unmodified fuel assemblies shown in figure I-4. However, each reflector has a removable 2.0-inch-diameter beryllium cylinder (similar to the one shown in the RD row of the 4 × 8 lattice in fig. I-2(b)), which is surrounded by a 0.075-inch annular cooling channel. These annuli are smooth and straight except for the complex inlet and outlet passages.

Control rods. - In figure I-5 are shown the essential features of the fuel-shim-safety rod. The beryllium safety rod differs in that a beryllium section is used in place of the fuel section. The beryllium section has a 2-inch-inside-diameter by 0.075-inch-thick annular cooling channel, which has simple inlet and outlet geometries. The beryllium cylinder is equipped with adapters for attachment to the tie rod of the cadmium section and to the lower section. The two 7/16-inch-diameter holes at the top end of the beryllium, fuel, and lower sections were to serve as catches for the handling tools; however, the core test findings later dictated that these holes be permanently sealed.

Cooling passages among reactor components. - Because of their importance to proper reactor cooling, attention is called to the set of cooling channels and clearance spaces between the core components. This set forms an eggcratelike labyrinth of interconnected channels; the most important are those that are located between a fuel assembly and an adjacent control rod, reflector piece, or another assembly. These labyrinth passages are shown in figure I-2.

Upper grid. - The upper grid serves two purposes: It centers the upper end of the assemblies and core reflector pieces to prevent side-to-side motion, and it supports the control-rod guide frames, which center the rods in position. The grid was designed to fit tightly around the top of the core box; however, there were five openings adjacent to the LA rods between the grid and side plate (fig. I-2(b)), which also had to be permanently sealed as a consequence of the core test results.

Lower grid. - The lower core grid supports the fuel assemblies, the core reflector pieces, and the lower control-rod guide tubes. The semicylindrical holes around the fuel assemblies and reflector pieces and the thin rectangular slots around the rods are the outlets for the water flowing between the core components.

Reflector lattice. - In the 4 × 8 reflector lattice all the pieces in a given lettered row are identical (fig. I-3), which is not true for the numbered rows because of the 9-inch-diameter cylinder (referred to as the horizontal through hole), which passes through the lattice. The lower grid supporting the lattice components also has openings that serve as coolant inlets to the spaces between adjacent reflector pieces. The upper grid of the 4 × 8 lattice is bolted in position so that only the cylindrical centers of each reflector piece are easily removable through the holes in the grid.

Flow-divider plate. - The flow-divider plate extends from the perimeter of the core and reflector pedestal to the perimeter of the plate that supports the upper thermal shields. Both the flow-divider and thermal-shields support plates are bolted in position and are perforated with round holes. The divider plate was specifically designed so the flow rate through the 4 × 8 reflector lattice could be adjusted to design values by merely changing the number of holes in it.

The holes in the thermal-shields support plate supplied water for cooling the shields.

General Flow Pattern

The general flow pattern within the reactor tank is illustrated in figure I-6. For full-power operation the coolant water is supplied by two of the three primary pumps. When the reactor is shut down, the afterheat is removed by the water supplied by the shutdown flow circuit. The water entering the tank is fed into the large plenum under the flow-divider plate around the core pedestal. It then flows upward by way of several parallel paths through the (1) 4 × 8 beryllium reflector lattice, (2) holes in the thermal-shields support plate, (3) holes in the divider plate, and (4) spaces at the joints where plates are bolted into position. The upward flowing water is dispersed in the large water volume above the core, from which it then flows downward through the core into the exit chamber below the pedestal.

The water entering the 4 × 8 lattice is divided at the lower grid into streams that feed the annular cooling passages inside the reflector pieces and the labyrinth of rectangular spaces between the pieces. It is quite obvious from figure I-2(b) that the flow pattern in the lattice is complicated because of the 9-inch-diameter through hole in it. As the water moves out of the lattice through the upper grid, it leaves as jets, which are dispersed in the large water volume above.

The water entering the core comes from what is essentially a large quiescent reservoir and, in doing so, experiences a sharp contraction. The flow feeds into the rods, the fuel assemblies, the reflector pieces, the labyrinth channels, and the cooling holes in the core-box side plates. The cooling water for inside the control rod enters the top of the cadmium section, which is usually more than 1 foot above the core during reactor operation. (Prior to any modifications all the water entering the rods did not pass through them because some of it leaked out through 7/16-inch handling-tool holes at the top of the beryllium, fuel, and lower sections into the channels around the outside of the rods.) The rod water finally discharges from the lower section into the core exit chamber. The water flowing through the inside of the fuel assemblies and reflector pieces is supplied through the square holes in the upper grid. Because of the high flow rate and the 90° corner on the grid hole the streams supplying the fuel assemblies undergo an additional contraction as they pass through the grid, thus creating a vena contracta inside the upper-end box of each assembly. The same is probably not true of the streams that pass through the grid holes above the reflector pieces because of their relatively low flow rates. None of the coolant flowing inside the reflectors and unmodified fuel assemblies leaked out because there were no openings along the length. Thus, all the water in the assemblies and reflector pieces flowed directly to the core exit chamber.

The labyrinth passages of the unmodified core received cooling water from (1) openings between the underside of the upper grid and the top of the fuel assemblies and reflector pieces, (2) five openings between the upper grid and the core side plate along the LA row (fig. I-2(b)), and (3) the handling holes in the control rods. One noteworthy characteristic of these channels is that they are interconnected with each other, the clearance spaces between the side support plates of the assemblies, and similar spaces. Hence, water can move freely in and out of the channels anywhere along the length depending on the local flow resistance, which is affected, for example, by variations in plate spacings. The water flow in the labyrinth channels is discharged out of the openings in the lower grid (fig. I-2(a)).

Flow Characteristics Measured

The hydraulic tests can be considered to be comprised of broadly five measuring problems, although the measurements were not made in the order given:

(1) The distribution of the bulk flow among the fuel assemblies and the fuel-shim-safety rods, and the total flow through the entire core

(2) The velocity distribution among fuel-plate cooling channels inside the fuel assemblies and the fuel section of the shim-safety rod, and the annular spaces of the reflector pieces in the core and in the 4 × 8 reflector lattice

(3) The velocities in the labyrinth channels that cool the outer surface of the end plates of the fuel assemblies - The flow around the outside of the reflector pieces, though important, is not as critical as around the assemblies and hence was not measured in this test

(4) Static-pressure distribution above and below the flow-divider plate and throughout the core - The pressure difference across the divider plate is the same as that across the 4 × 8 reflector lattice; the static pressures throughout the core were important to the flow in the labyrinth of channels around the outside of the components and the structural integrity of the end fuel plates

(5) The transient flow rates in the fuel assemblies during the coast-down period after the primary pumps are shut off. Knowledge of the transient flows is necessary for assessing the temperatures in the core and reflector due to the fission product decay heat generated after the reactory is shut down

Instrumentation

Two techniques were considered for measuring the flows in the cooling channels of the assemblies and reflectors (items (2) and (3) of the preceding section) - the conventional total-pressure and static-pressure probes and the salt-solution methods. A total-pressure tube measures the static plus dynamic pressures. When alined in a well-defined flow stream such as in a long pipe whose cross-sectional dimensions are large compared with the tube diameter, the tube measures the total pressure at the point where it is located. If the static pressure is known at the same location, then the velocity can be calculated from the measured difference of the total and static pressures. Hence, the velocity profile in the stream can be accurately measured, and from it the average velocity can be calculated.

For the hydraulic tests in the PBR, the problem was to measure the average velocity in a channel using only one fixed probe. The validity of this method is based on the assumption that the velocity profile is well known at the duct cross section where the probe is located. The fully developed velocity distribution in rectangular and annular channels such as those in the PBR is well known. Thus, the velocities measured at any point can be related to the average velocity over the cross section. Measuring the velocity at a point in a fuel-plate channel is difficult because the probe diameter cannot be made negligibly small compared with the plate spacing and still have short response time. Hence, a larger diameter tube must be used. Such a large probe no longer senses the total pressure at a point, instead it senses some average value over the probe opening. For example, in the idealized case of fully developed turbulent flow in a channel of infinitely wide parallel plates (aspect ratio = ∞), the ratio of the average to maximum velocity is 0.87 (ref. 9), where the maximum is at the mid-plane between the two walls. If a probe with diameter of, for example, 40 percent of the distance between the plates were placed at the center, the indicated velocity would no longer be the maximum but, rather, a smaller value. The ratio of the average to indicated velocities would therefore be somewhat greater than 0.87. This ratio is also affected by the facts that a fuel-plate channel has a finite though large aspect ratio and that the probes may not be alined in the exact center. Hence, to use these probes with reasonable accuracy it was necessary to ascertain the ratio of the true average to the indicated velocity.

The salt-solution technique employs two electrodes that are mounted in a flow channel with one electrode spaced a known distance downstream from the other. These electrodes sense the change in resistivity of the surrounding water. A slug of salt solution such as potassium nitrate is injected into the moving water stream at a point upstream from the first electrode. As the solution passes the first electrode, a timer is started; when it passes the downstream electrode, the timer stops. In theory the average velocity is the ratio of the spacing between the electrodes to the measured time. The accuracy of this method was found experimentally (in a laboratory lucite model of a fuel cooling channel) to be dependent on the turbulence level, the dilution of the salt-solution slug, the manner in which the injection of the solution disturbed the flow pattern, and many other factors. Because time did not permit developing this technique, it could not be used with complete confidence. Hence, the method was incorporated into the reflector annuli flow measurements as a backup system to the total-pressure probes for the shutdown flow conditions; however, it was never used.

INSTRUMENTED COMPONENTS

Instrumented Fuel Assemblies

Figure I-7 shows details of the total-pressure tubes and the static-pressure probes that were employed to measure the velocities among the cooling channels of the fuel assemblies. The figure also indicates how the probes were mounted in position at the outlet end of the fuel section. To reduce the response time, 0.090-inch-outside-diameter pressure leads were soldered to the probes at the shortest distance from the probe tips as was practical. The pressure leads had to be flattened because of space limitations and were fastened to the outside of the end plates by an epoxy cement containing 80 percent powdered aluminum. The leads were brought up into the handling-tool recesses and then allowed to extend straight above the top of the assembly (fig. I-8). The stainless-steel pressure leads ended approximately 9 inches above the core and were connected to 1/8-inch-inside-diameter thick-walled neoprene rubber tubing, which later in the test program was changed to a tough plastic tubing of thinner wall. The stainless-steel pressure leads could have been made much longer if it had not been for the manner in which the upper-core grid was removed. This longer length would have been desirable because the stainless-steel tube to rubber joints formed a bundle approximately 2 inches in diameter, which could be a sizable flow obstruction if it were too close to the grid. One dummy fuel assembly was equipped as shown in figures I-7 and I-8.

For the velocity measurements in the labyrinth channels outside the fuel assemblies' end and side plates and for static-pressure measurements along the length of the inside and outside, total-pressure tubes and static wall taps as shown in figure I-9 were used. These were located at positions approximately level with the top and bottom edges of the internal fuel plates (figs. I-13 to I-17). The pressure leads again were 0.090 inch in outer diameter and were led through the inside of the assembly and then out the top of the upper-end box. Several assemblies were employed during the tests that had one or more impact tubes located at each level to reduce the testing time and to get more detailed measurements.

Simulated Fuel Assemblies

The steady and transient coast-down flow rates through the inside of the fuel assemblies were measured with a pair of simulated assemblies each containing a special turbine flowmeter. The design, laboratory testing, and application of these instruments are discussed in detail in part III.

Instrumented Fuel-Shim and Beryllium Rods

The flow characteristics of the fuel section of a fuel-shim rod were determined using both laboratory and core test results. The overall pressure loss of a rod is a sum of the losses of the cadmium, fuel, and lower sections. The pressure loss of the cadmium section is affected by the flow conditions at its inlet, and for this reason the cadmium loss as measured in a laboratory test loop may not be the same as in the core for a given flow rate. The turbulent mixing that occurs as the water flows through the long complicated passage inside the cadmium section removes the effect of the inlet conditions before the water arrives at the fuel-section inlet. As a consequence, the pressure loss and the flow distribution among the channels of a fuel section for a given bulk flow rate are the same whether the rod is in a laboratory test loop or in the reactor. This fact was used to good advantage in the core tests to simplify the measurement problem.

The fuel section of one shim rod was instrumented with two wall static-pressure taps inside, one a short distance upstream and the other a short distance downstream of the fuel section. The lead from the downstream tap was flattened and cemented to the outside of the fuel section and then brought inside at the top. Then both leads were led through the inside of the cadmium section and out the top where they were joined to strong plastic tubing 1 foot beyond the top. This fuel section along with a cadmium section was calibrated for the pressure loss against flow rate in a laboratory test loop (part II). Thus, by measuring the fuel-section pressure loss in the core, the bulk flow rate through the fuel section is established from the calibration curve.

A second fuel section of shim rod was tested in the laboratory for the velocity and static-pressure distributions among the cooling channels (part II). These distributions were measured for a wide range of bulk rates. Hence, once the bulk rate was measured with the instrumented section described in the previous paragraph, the velocity and static-pressure distributions were known.

A third fuel section of a fuel-shim rod was instrumented internally with total-pressure tubes only in a manner similar to a fuel assembly (fig. I-7). The severe space limitations would not permit installation of the static probes; therefore, only a relative distribution of total pressures could be measured. The stainless-steel pressure leads were cemented to the outside surface of the fuel section and then led back inside at the joint between the cadmium and fuel sections. The leads were then encased in two 7/16-inch-diameter tubes, which were held in the cadmium section and brought out the top where they were joined to strong plastic tubing 1 foot beyond the inlet.

A static-pressure probe was mounted in a beryllium shim-safety rod a short distance above the beryllium section to measure the pressure at that point.

Dummy Reflector Components

The water velocities in the annuli of the reflector pieces were measured with the total-pressure probe and wall static-pressure tap combination located near the outlet end of the annuli. A wall static tap was also located upstream so the frictional pressure loss could be measured and compared with the value calculated from the measured velocity. The total-pressure probes and wall taps were mounted on stainless-steel dummy cylinders that were identical to those of beryllium. One dummy cylinder was needed for the core reflector pieces, one for the RA, RB, and RC rows, and one for the RD row of the reflector lattice. Because the RA, RB, and RC rows had such irregular passages, four total-pressure probes were mounted 90° apart on a short cylindrical plug that fitted all three rows. In this way a meaningful average velocity could be measured. No static-pressure losses could be measured in the RA, RB, and RC annuli. Also no velocity or static-pressure measurement could be made in the annuli below the horizontal through hole or in the flat rectangular channels outside the 4 × 8 lattice pieces because of the extreme complexity of the geometry.

Instrumentation on Flow-Divider Plate and Core Exit Chamber

Static-pressure taps were mounted on the flow-divider plate both on the top and undersides at five locations, four around its perimeter and one next to the core. The taps were for measuring pressure distributions on the plate and the pressure loss through the plate and the 4×8 lattice.

One permanent tap was placed in the flange of the core pedestal to measure the static pressure of the core exit chamber. This latter tap and one of those on the upper side of the flow-divider plate were used to measure the pressure loss across the core.

Pressure Measuring Instruments

The various pressure differences were measured with two different systems. One was a combination of differential pressure gages for data to be recorded at the higher flow rates. The other was a group of inverted manometers. The manometer system was primarily for measuring the small pressure differences encountered at the shutdown flow rates. Both systems were mounted on a large portable console, and each could be operated independently of the other. The gages, capable of operating at pressure levels up to 500 pounds per square inch gage, were of several different ranges from 0-5 to 0-50 pounds per square inch with 1 or 2 percent of full scale as a least count. All the gages were new, and their calibrations were checked on deadweight testers. The manometers were 130 inches tall with the smallest scale increment of 0.1 inch. A nitrogen supply system was used to maintain the water columns within readable range in the manometers during the tests at shutdown flow conditions.

Instrumentation Leads

All the pressure leads exiting from the core and reflectors were of stainless-steel tubing joined to neoprene rubber or tough plastic tubing at a distance far enough from the top of the grid to prevent blockage of the flow. To prevent breakage, the leads from each core and reflector component were wrapped in a fairly tight bundle with black plastic electrical tape. The bundles were lashed to 1/16-inch-diameter support cables whose lower ends were fastened to the particular components in the core and the upper ends to a frame in the tank hatch. The cables and attached bundles were held taut during the tests to prevent excessive vibration and whipping. The leads from the control rods were held taut by a special pulley and weight arrangement that permitted the rods to be moved at any time without any slack in the pressure lead lines. The rubber and plastic leads were then connected to 1/4-inch copper tubes, which led out of the tank through blind flanges on a series of 3- to 6-inch pipes at the top of the tank. The copper pressure leads were fastened to a bulkhead from which they were brought to the portable console containing the pressure gage and water manometer systems. Each pressure lead was teed with one branch going to each system. The lines on the console were arranged with proper valving so the pressure difference between almost any pair of pressure probes or taps could be measured on a gage of suitable range. The pressure leads from the flow divider plate and the core exit chamber were all 1/4-inch-outer-diameter stainless steel extending from the tap locations out of the tank to the bulkhead. One important criterion met by all the pressure leads coming out of the tank was that their diameter was sufficiently large to give fast response at the pressure gages. Fast-responding instrumentation was important not only to the data accuracy but to the testing time as well.

Flow Pattern Visualization Techniques

To visualize the flow patterns in the reactor tank, underwater lights were used for illumination. Several large-diameter flanged ports in the tank top were fitted with quartz viewing windows. Pieces of white nylon cord 6 to 10 inches long from an obsolete parachute were fastened in many places in the tank on the core, the pressure leads, the thermal shields, and so forth. Some movies of the flow pattern were recorded.

Laboratory Tests

The laboratory experiments conducted on the fuel-shim-safety rods, dummy, and simulated fuel assemblies were performed in a laboratory flow loop. The details are given in parts II and III.

TESTING PROCEDURE

To start any test run, the instrumented core and reflector components had to be installed in predetermined positions. Then the pressure lead lines and their support cables were made taut by fastening them at the tank hatch. The tank was then sealed, filled with water, and pressurized; and the flow was started. All pressure lines were bled until no air was present. The manometers were particularly useful for visually checking for the presence of air in the lines. Once the lines were clear, the system was ready for data recording. For the measurements at high reactor flows where only the pressure gages were used for measuring differences, data recording was merely a question of connecting the desired lines to each side of a gage of the proper range by a valving system and reading the indicated value. This was done for each pair of taps whose pressure difference was wanted.

For shutdown flow measurements, only the manometer system was capable of measuring the small pressure differences. After the lines were clear of air and with no flow in the system, the water levels in the manometer tubes were allowed to level out to some constant value as a further check for the presence of air bubbles in the lines. If all water columns were at the exact same height to within 0.05 inch, the shutdown pumps were started. Twenty to thirty minutes were allowed for the water columns to reach their equilibrium level. All the manometer readings and other test data were recorded. The pumps were then turned off, and the manometers were allowed to settle for a recheck on their zero level.

Transient flow measurements with the simulated fuel assemblies were made at the end of a run at full-flow condition. No shutdown pumps were running. The strip-chart recorders, which registered the outputs of the turbine meters, were turned on. Then the power to the two primary pumps was turned off. The flow rate against time characteristic was automatically traced on the strip charts.

DATA PROCESSING

The methods for processing the data were straightforward for all the measurements. The methods used for the total- and static-pressure probes need to be elaborated upon.

The velocity V indicated by a total-pressure tube in a large well-defined flow stream is given by the formula (ref. 10)

$$V = \sqrt{\frac{2}{\rho} (P_t - P_s)}$$

where

ρ density of flowing stream

P_t total pressure sensed by velocity probe

P_s static pressure at same location

When a velocity probe is placed in a small passage such as a reflector annulus, the velocity indicated by the probe is related to the true average value at that cross section by some factor F. Hence, the formula becomes

$$V_{av} = F \sqrt{\frac{2}{\rho} (P_t - P_s)}$$

where F depends on the location of the probe in the cross section, the ratio of probe diameter to channel wall separation, the flow stream definition, and the Reynolds number. For these flow tests the velocity probes were located very near the midpoint between the walls of the rectangular channel inside a fuel section or a reflector annulus. Some values for F were determined from the measurements of the flow distribution among the channels inside the fuel assemblies made in the laboratory tests prior to the core tests. For the rates expected at full-power operation of the reactor, an average $F = 0.91$ (channel Reynolds number $\geq$ 50,000) was measured and used until careful tests on a lucite model of a rectangular channel resulted in a value $F = 0.87$ (discussed on p. 20). An experimental value of F at reactor shutdown flow conditions could not be obtained because of certain equipment limitations. The Reynolds numbers for shutdown rates in the cooling channels were in the transition range of 3000 to 9000. For laminar flow in thin annuli and infinite parallel plate channels, the value for F is 0.66 (ref. 9). Hence, for these low flows a value $F = 0.75$ was chosen as a reasonably good conservative estimate.

The friction pressure losses in the reflector annuli were calculated from the following standard equation for steady flow in long straight channels of constant cross section (ref. 11):

$$\Delta P = 2f \frac{L}{D_e} \rho V_{av}^2$$

where

ΔP static-pressure difference between two axial positions separated by a distance L

f friction factor

L distance

D_e equivalent diameter defined as the ratio of four times the cross-sectional area to the wetted perimeter

ρ fluid density

V_{av} average velocity measured by probe

For smooth passages the formula (ref. 11)

$$f = \frac{0.046}{Re^{0.2}} \qquad \text{for} \quad 10^4 < Re < 10^5$$

was used where Re is the Reynolds number. The friction pressure loss calculated by the formula was compared with the measured value. The volume rate of flow through the annuli was computed from

$$Q = AV_{av}$$

where

Q volume rate

A cross-sectional area

These formulas were also used to estimate the flow through the long round cooling holes in the core side plates on the assumption that the measured core pressure loss was equal to the ΔP of the equation.

The flow rates through the turbine meters of the simulated fuel assemblies were determined from the measured frequency output of the meters and the manufacturer's calibration curve of flow against frequency. This calibration curve was checked independently at the Lewis Research Center.

The water rates through the holes of the flow-divider plate and thermal-shield support plate were calculated by treating each hole as an orifice plate inside a pipe whose diameter was approximately equal to the spacing between hole centers. The volume flow rate Q_O through an orifice plate is related to the measured pressure difference ΔP_O across the plate by the expression (ref. 10)

$$Q_O = A_O V_O = A_O C \left\{ \frac{2\ \Delta P_O}{\rho \left[1 - (A_O/A_p)^2 \right]} \right\}^{1/2}$$

where

V_O average velocity through hole

C discharge coefficient

A_O/A_p ratio of orifice hole area A_O to pipe area A_p

When this equation is used to calculate the flow through a perforated plate, Q_O is the volume flow rate per hole and ΔP_O is the pressure difference across the plate. The ratio A_O/A_p is approximated by the ratio of the total area of the holes to the area of the solid plate. The quantity $(A_O/A_p)^2$ for the flow-divider plate in the PBR was usually very close to zero.

Calculations were made of the overall pressure loss for the entire reactor and for a typical fuel assembly when in the core and in the laboratory test loop. Although lengthy and detailed, the calculations were straightforward. All flow passages in the core and in an assembly were viewed whenever possible in terms of the most common types such as sudden and gradual contracting and expanding passages, long straight channels of constant cross section, and so forth. The formulas used for calculating the pressure losses of these various channels as a function of flow rate are available in any good fluid mechanics handbook or text. For this reason, no details of the computational procedure are given here.

TEST RESULTS AND DISCUSSION

The hydraulic test results are, for clarity, presented and discussed as five separate parts: (1) the tests in the unmodified core, (2) the nature of a flow deficiency uncovered in the core and its causes, (3) the modifications made to eliminate the flow problem, (4) the influence of the modifications on the core flow characteristics, and (5) other important test results and comments. Each of these phases will now be discussed in detail. The water temperature for all tests was held between the limits of 65° and 93° F.

Results of Tests on Unmodified Core

Adjustment of flow-divider-plate pressure drop. - The first tests to be run were for adjusting the flow-divider-plate pressure loss so adequate coolant flowed through the 4 × 8 reflector cooling passages. The pressure distributions on the top and bottom side of the plate were very uniform. One unexpected result was that a large amount of water was leaking from the underside to the topside of the metering plate. A series of tests were made with the 4 × 8 lattice sealed so no water flowed through it, and the results verified the existence of the leakage and the validity of the calculations for the flow through the round holes in the plate. It is believed that the leakage occurred at the bolted joints of the divider and thermal-shield plates. As a result of the leakage, the number of $1\frac{1}{4}$-inch-diameter holes was reduced from an expected 100 or so to 10 holes $1\frac{3}{8}$ inch in diameter. In spite of the leakage the driving pressure difference available across the lattice was sufficient to provide the water rates needed to cool all the lattice pieces.

Reflector lattice. - The velocity distributions measured inside the annuli of the 4 × 8 reflector lattice were reasonably uniform considering the lack of uniformity in geometry. For example, with a lattice pressure loss of 12.5 pounds per square inch most velocities were in the range 14 to 20 feet per second. The measured frictional loss in the annuli of row RD usually agreed with the calculated value based on the measured velocity to within 6 percent. The velocities measured by the four probes in the annuli of rows RA, RB, and RC deviated less than ±2 feet per second at an average of about 18 feet per second. Although no measurements were made in the interconnected rectangular passage between the pieces and the annuli of the RA, RB, and RC rows under the horizontal through hole, it was estimated that velocities there were comparable to those measured in the annuli. The bulk flow through the 4 × 8 lattice could only be determined in an approximate way during the tests in which the lattice was sealed. The rate agreed fairly well with the value calculated assuming all the lattice components were like those in row RD. Thus, the tests show that the flow characteristics of the 4 × 8 lattice were quite satisfactory.

Reactor core and core components. - The flow characteristics of the core were in excellent agreement with the design specifications except for the flow deficiency found in the labyrinth channels. The bulk flow against pressure loss for the core is given in figure I-10, where the data are compared with the curves calculated for water temperatures of 50°, 70°, and 170°. The bulk flow distribution among the fuel-assembly positions of the core as measured by the simulated fuel assembly was uniform to within a maximum deviation of ±3 percent of the average at the design core flow of 15,500 gallons per minute. The maximum of 485.6 gallons per minute occurred in LB-6, while the minimum of 458.6 was measured in LD-2. The bulk rates through the unmodified rods were in the range of 380 to 400 gallons per minute. The transient measurements showed that the bulk flow rate coasted to 10 percent of its full flow value within 15 seconds after the two primary pumps were turned off simultaneously (see part III).

The velocity, static-, and total-pressure distributions among the fuel cooling channels inside the fuel assemblies are shown in figures I-11 and I-12. These figures are representative of a large amount of data. The static- and total-pressure distributions are relative values in that each was measured using the probes in channel 1 as a reference. However, for the velocity calculations the difference between the total and static pressures in each channel was used.

The nonuniformity of velocity and total-pressure distributions in some core positions such as LB-2 is evident in figure I-11(a). These data indicate the asymmetry of the flow stream entering the upper grid propagated into the cooling passages. The asymmetry is undoubtedly caused by the sharp turning of the water as it enters the grid hole above the assembly in those positions. This condition probably exists in all the positions of rows LA and LD but is not reflected in the velocity distribution measurements because of the direction in which the plates were alined relative to the incoming flow direction. The influence of the control-rod extensions on the flow distributions was found to be minor as shown in figure I-11(b), which is representative of many similar measurements. The distributions at shutdown flow conditions shown in figure I-12(b) were uniform and adequate in magnitude.

Figures I-11 and I-12 (as well as figs. II-4, II-5, and II-7) show that the static pressure near the exit of the fuel cooling channels was not constant from channel to channel. The magnitude of this static-pressure variation was not generally negligible compared with magnitudes of the total minus static pressures. As a consequence, it was necessary to employ both a total-pressure probe and a static-pressure probe in each channel in order to measure the average flow in it with reasonable accuracy.

The hydraulic characteristics of the fuel-shim rod were in accord with design specifications in spite of the fact that some water was leaving the interior through the open handling-tool holes upstream of the fuel section. The calibrated fuel section indicated that the bulk flow rate ranged from 380 to 400 gallons per minute depending on which core lattice position the rod was situated and how far the rod was extended into the core. The velocity ranged from a minimum of 25 feet per second to a maximum of 30 feet per second. The distributions were very similar to those shown in figure II-7 except that the magnitudes were slightly lower. The total-pressure distributions measured in the core with the fuel section containing only total-pressure probes and one static tap were similar to those measured in the laboratory. This latter fuel section was used to check the validity of the argument that the cadmium section smoothed out entrance flow effects. In one of several core tests with the fuel section, half of the cadmium inlet was blocked. The resultant total-pressure distribution was unaffected, although the magnitude was lower because of the choked inlet.

The static pressures inside and outside along the length of the assemblies are shown in figure I-13. These data were measured in the core after the modifications were made and will be discussed further in the report (p. 18).

The flow rates in the annuli of the core reflector pieces were adequate, and the measured friction pressure losses agreed within 5 percent with the calculated value based on the measured velocity. The flow distribution among the annuli of the different pieces in the core was uniform to within a maximum deviation of approximately 10 percent of the average of 35 gallons per minute. The control-rod extensions had little influence on the flow in the annuli.

The flow rate through the beryllium shim-safety rod was comparable to that in the annuli of the core reflector pieces. Because the cross-sectional flow areas inside the cadmium and lower sections were many times that of the annulus in the beryllium, the measured pressure loss through them was negligible. Hence, the flow rate through the beryllium cooling annulus was easily calculated assuming that the full core pressure difference was available for driving the water through it.

Flow pattern in reactor tank. - The general flow pattern in the tank was easily visible with the help of the nylon cords. When the reactor was designed, there was some concern about how the water flowing up through the 4 × 8 lattice would influence the water flow distribution into the core. The flow from the tank into the core was like that of a very large container draining into a much smaller opening. The region of strong flow extended 12 to 18 inches above the core where the velocities of the contracting stream were the highest. Essentially the stream entering the core behaved as though there were no flow out of the lattice. The contracting core stream could be seen breaking up the jets of water issuing from the various reflector positions in the lattice. This was visualized by injecting air bubbles into the coolant annuli via the pressure taps in dummy instrumented cylinders. Those bubbles rising out of the rows closest to the core were promptly swept into the core. In the region above the contracting core stream the nylon cords indicated that the motion was largely turbulent mixing.

Some tests were run with and without the large vertical test columns in position against the core. The results showed that their presence did not influence any of the flow distributions in the assemblies or any other hydraulic characteristics elsewhere in the core.

Core Flow Deficiency and its Causes

The only serious flow deficiency found while testing the core occurred in the labyrinth cooling channels outside the end plates of the fuel assemblies. Basically the anomaly can be summarized as follows: (1) The inlet velocities as measured near the upper end of the fuel plates were in the range 15 to 22 feet per second, too far below the minimum desired value of approximately 27 feet per second, and (2) the outlet velocities and static pressures at the lower end of the fuel plates varied as the rods were raised. These outlet velocities fluctuated widely and in a random fashion about an average of approximately 30 feet per second, whereas the static pressures always decreased by about 4 pounds per square inch. The largest changes occurred when the rods were raised 6 inches. It was this flow problem that had to be eliminated to prevent restricting the power level of the reactor. Many additional tests were run in an effort to uncover the cause of the difficulty, and the results are far too numerous to include here. Hence, the following discussion will be limited to the direct causes of the problem, the modifications needed to correct the flow, the influence of these modifications on the core characteristics, and other pertinent observations.

A number of factors were found to contribute directly to flow starvation and fluctuations in the velocities and static pressures. Excess water was pouring into the labyrinth channels from inside the control rod through the handling-tool holes in the beryllium, fuel, and lower sections of the control rods causing a pressure buildup in the channels. This excess water from the rods also explained the cause of the velocity fluctuations and the static-pressure decrease at the outlet end of the channels as the rods were raised. The pressure buildup contributed in part to the starvation at the inlet end. In addition, the five openings along the LA row between the upper grid and the core side plate were probably feeding extra water into the labyrinth. Part of the water between the core-box side plate and the reflectors flowed into the channels around the fuel assemblies in an effort to equalize the pressures and thereby in part contribute to the low velocities at the inlets. Extra water was also entering the labyrinth from around the core reflector pieces because the pressures under the grid, due to the low flow into the grid holes above a reflector, were considerably higher than at fuel-assembly positions. Finally, the flow resistance on the outside of the upper-end boxes of the assemblies was found to be too high, and, in addition, the inlet to the passages was in the low-pressure region of the contracted water stream entering the inside of the upper-end box. Time did not permit testing for the magnitude of the influence that each factor contributed; hence, changes were made to ensure elimination of the problem.

Core Modifications and Design Changes for Eliminating Flow Anomaly

The following modifications were made to the core:

(1) All holes in the control rods were sealed as were those openings adjacent the LA row between the upper grid and the core side plate.

(2) Restrictions were placed in the upper grid holes above the core reflectors. (Tests subsequent to this work showed these to be unnecessary.)

(3) A 2-inch-diameter hole at 45° to the fuel-assembly centerline was bored upward into each side of the upper-end boxes (fig. I-14).

To provide additional pressure potential, the bulk flow through the primary loop was raised from the design value of 15,500 to 17,700 gallons per minute.

Influence of Modifications on Flow Characteristics

The modifications to the core, in addition to correcting the flow anomaly, improved other flow characteristics without producing any adverse flow problems. The openings in all the upper-end boxes in the core created a plenum of nearly uniform pressure above the fuel plates. In one assembly the velocities measured in only channels 1 and 17 were more nearly equal at many core positions than those measured with the unaltered end boxes. Hence, the plenum tends to promote a more uniform flow distribution inside the assemblies. The static pressures along the inside of the assembly (fig. I-13) were unaffected by the presence of the openings, although figure I-13 presents only the data on the modified core. The agreement with the calculated pressure changes is good.

From figure I-13 the importance of the openings is seen in the fact that the channels outside the assemblies have their inlet in the higher pressure region just above the plates, whereas without the openings the inlets were in the low-pressure region at the top of the assembly. Nowhere along the end plates were the pressure differences from inside to outside of the plates excessive; thus, the possibility of buckling them was reduced. Sealing the holes in the control rods eliminated the fluctuations in the velocities and static pressures. Also, the sealed rod holes and the sealed openings between the upper grid and core box undoubtedly reduced the pressure buildup in the labyrinth passages and flow starvation in them. The increased total core flow rate increased the velocities in the starved channels as well as in all other passages of the core. No measurements were made with the simulated fuel assemblies in the modified core. However, because the velocities and static pressure inside the fuel channels were not adversely affected by the modifications, it appears certain that bulk flow distribution among the assemblies was not altered significantly.

Additional Results and Discussion of Flow in Labyrinth Channels

A large number of velocities were measured in the labyrinth channels throughout the modified core, and these are shown in figures I-15 to I-17. Also included are the data that were questionable for reasons noted on the figures. The significant thing to note is that the velocities at the inlet were usually lower than those at the outlet. The reasons for this are given as follows.

The flow characteristics of interconnected channels of different cross-sectional area having the same inlet and outlet plenum chambers are not the same as when the same channels are isolated. Proof of this is given in reference 12 (pp. 11 and 12). Two thin rectangular channels 3 inches wide by 0.071 and 0.135 inch and 38 inches long were separated by a 1/8-inch plate and were tested for static pressures along the length under two conditions. In one test the channels were not connected, and in the other test two rows of 0.026-inch-wide slots were cut lengthwise in the separating plate. The inlet and outlet of each were open to common plenum chambers. In the test with isolated passages the narrow channel had a higher static pressure everywhere along the length than the wider one. When the passages were interconnected, the pressure was only slightly higher in the narrow channel. Also, the overall pressure difference needed to push a given rate through the interconnected channels was higher than if the channels were isolated from each other. The total flow rates in the two tests were identical. A study of the results shows that the velocity in each channel was not constant along the length; rather, the narrow channel was pumping water into the wider one. Hence, the outlet velocity in the larger channel was greater than at the inlet. All the curved cooling channels and the flat clearance spaces of the egg-crate labyrinth of the core do not have the same nominal spacing. For example, the spacing between the outer surface of the end plate of two adjacent assemblies is nominally 0.115 inch, whereas clearance space between the side plates of two assemblies is nominally 0.075 inch. Hence, it can be concluded that higher velocities at the outlet of the cooling channels occur because each channel is not isolated from the surrounding ones. The bulk of data taken in the modified core tests tends to support this conclusion.

Other factors influenced the velocities in the labyrinth channels. The spacing between the end plates of two adjacent assemblies varied considerably about the nominal value. A large number of measurements were made along the outer surface of the end plates of each dummy assembly using a jig and micrometer, and these measurements permitted the calculation of the local plate spacing between any two assemblies. A typical set is shown in table I-I. The large local spacing variations tend to produce local pressure differences that tend to even out by inducing crossflows. Such local pressure gradients did exist and were easily measured. Local pressure gradients among the labyrinth passages are also induced by complex inlet and outlet geometries and the asymmetry of the core geometry. For example, the flow resistance through the lower grid was not uniform and could have propagated upstream to influence the flow distribution. The rivet indentations on the cadmium sections of the rods present an additional drag on the flow, but the effect was not measured. Thus, it is seen that hydraulic characteristics are influenced by many factors and that detailed measurements are necessary to assess these characteristics.

At one time during the tests, before the causes of the flow deficiency were found, the inner diameters of the lower-end boxes on the fuel assemblies were reduced in an attempt to eliminate the starvation in the labyrinth channels by increasing the core pressure drop. Decreasing the inner diameters caused the pressure on the inside of the lower-end box to rise to over 10 pounds per square inch above the pressure on the outside of the end plates at the lower end. With this condition it was thought that the higher velocities at the outlet of the labyrinth channels were caused by an outward deflection of the end plates. A bench test was set up in which an assembly was pressurized internally, and the end-plate deflections were measured. The results of the bench test, presented in figure I-18, show that the deflections are small except at large pressure differences across the plate. According to reference 1, pressure differences of 11 pounds per square inch across the end plates of MTR fuel assemblies caused the concave plate to buckle. To eliminate the danger of buckling the plates, the area inside the lower-end box of the MTR assemblies was increased to reduce the end-plate pressure difference. The PBR core test results confirmed the MTR findings, and the inner diameter of the lower-end boxes of the PBR assemblies was retained as originally designed.

Accurate measurement of the minimum average velocities in the labyrinth channels was a difficult task because the velocity distributions at the cross sections are not well known for the reasons mentioned previously. Some uncertainties existed because the channel spacings at the probe locations were so widely variant and because the flow may not have been in line with the probes. Hence, the ratio of the average to indicated velocities was somewhat in doubt because the probe was probably not at the center plane between the channel walls most of the time. A careful laboratory test of a single velocity probe inside a well-defined rectangular channel 0.115 by 2.62 by 30 inches showed that the ratio of average to indicated velocities was minimum, 0.87, at the channel center and increased to a value near 1.00 when the probes were against the wall. Hence, all the velocities shown in the figures I-11, I-12, and I-15 to I-17 were calculated using $F = 0.87$ instead of $F = 0.91$. The influence of probe misalinement was also checked and found to be nil except for misalinements beyond 20°. A yawed probe will always indicate a lower velocity than one directed into the stream. Thus, by using the assumption that the probes in the labyrinth channels were always centered and alined, the average velocities calculated from the probe readings tended to be conservative.

CONCLUSIONS

The hydraulic characteristics of the NASA Plum Brook Reactor were measured in detail with instrumentation developed for this purpose. Total- and static-pressure probes were used to measure velocities in the cooling channels inside and outside the fuel assemblies, fuel section of the fuel-shim-safety rods, and beryllium reflector pieces. A pair of special simulated assemblies, each of which contained a turbine flowmeter, were developed and employed to measure the bulk rate through the inside of each assembly position of the core at steady flow and during the transient period of coast down. Static-pressure wall taps and probes were also installed to measure the static-pressure distribution in the active core and other components of the reactor tank. Commercial pressure difference gages and inverted glass manometer tubes were used to measure the many pressure differences. Some visual observations were made of the flow patterns in the water volume above the core with the help of nylon cords and underwater lights. Most of the tests were run at expected full power or shutdown flows in the temperature range from 65° to 93° F.

The performance of the instrumentation was most satisfactory. The velocity probes measured the true flow through the well-defined passages such as those inside the assemblies and reflector annuli to within ±2.5 percent. In the channels where the flow profiles were not very well known, the probes were valuable because they indicated velocities that were conservative. The static-pressure taps and total-pressure probes likewise gave accurate data. The simulated assemblies measured the true bulk flow through them to within 1 percent both for the steady and transient coast-down flow conditions. The reliability and accuracy of the simulated assemblies and the velocity and static-pressure probes make them suitable for use in hydraulic testing in other nuclear reactors, particularly those with plate-type assemblies.

The hydraulic characteristics of the NASA Plum Brook Reactor were in satisfactory agreement with the design specifications except for an unexpected flow deficiency in the eggcratelike labyrinth of interconnected passages between the core components. By some relatively simple modifications the flow anomaly was corrected. The velocity distributions among the important cooling channels of the core were reasonably uniform. The static pressures were favorably distributed so as to eliminate the danger of collapsing any fuel assemblies due to the hydraulic forces. The motion or position of the control rods had very little influence on the flow and pressure characteristics. Inside the cooling channels of the labyrinth the flow patterns were not the same as they would be if the channels were not connected; hence, the rate through such channels cannot be easily calculated. The modifications to the core in addition to correcting the flow problem did not produce any adverse effects; rather, some improvements resulted. Thus, the hydraulics of the modified NASA Plum Brook Reactor satisfy all of the flow requirements for full-power and shutdown operations.

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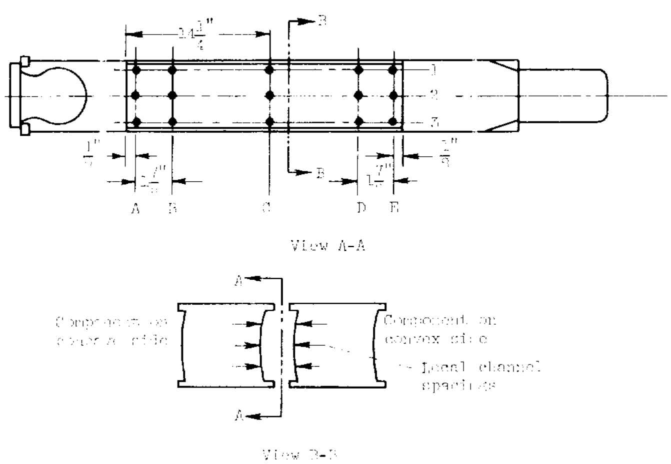
TABLE I-I. - MEASURED LOCAL CHANNEL SPACINGS BETWEEN FUEL ASSEMBLIES AND ADJACENT ASSEMBLIES AND CORE REFLECTOR PIECES

[All dimensions in inches.]

Component on concave side	Core reflector	F.A. I	F.A. III	F.A. IV	F.A. VI	F.A. VII	F.A. VIII
Component on convex side	**F.A. I**	**F.A. II**	**F.A. IV**	**F.A. VI**	**F.A. VII**	**F.A. VIII**	**F.A. IX**
A1	0.097	0.157	0.139	0.132	0.126	0.166	0.109
A2	.100	.140	.123	.121	.123	.151	.101
A3	.095	.139	.129	.121	.115	.144	.090
B1	0.086	0.137	0.130	0.139	0.117	0.139	0.085
B2	.091	.130	.146	.132	.111	.132	.093
B3	.083	.121	.133	.120	.105	.136	.085
C1	0.096	0.126	0.128	0.145	0.143	0.107	0.109
C2	.096	.122	.131	.140	.138	.100	.113
C3	.092	.113	.124	.122	.139	.100	.106
D1	0.094	0.129	0.124	0.129	0.121	0.120	0.115
D2	.091	.125	.120	.120	.107	.109	.119
D3	.086	.111	.116	.117	.117	.115	.111
E1	0.102	0.133	0.115	0.107	0.113	0.134	0.115
E2	.098	.120	.116	.129	.102	.117	.119
E3	.084	.112	.106	.110	.101	.123	.116



Measurement positions

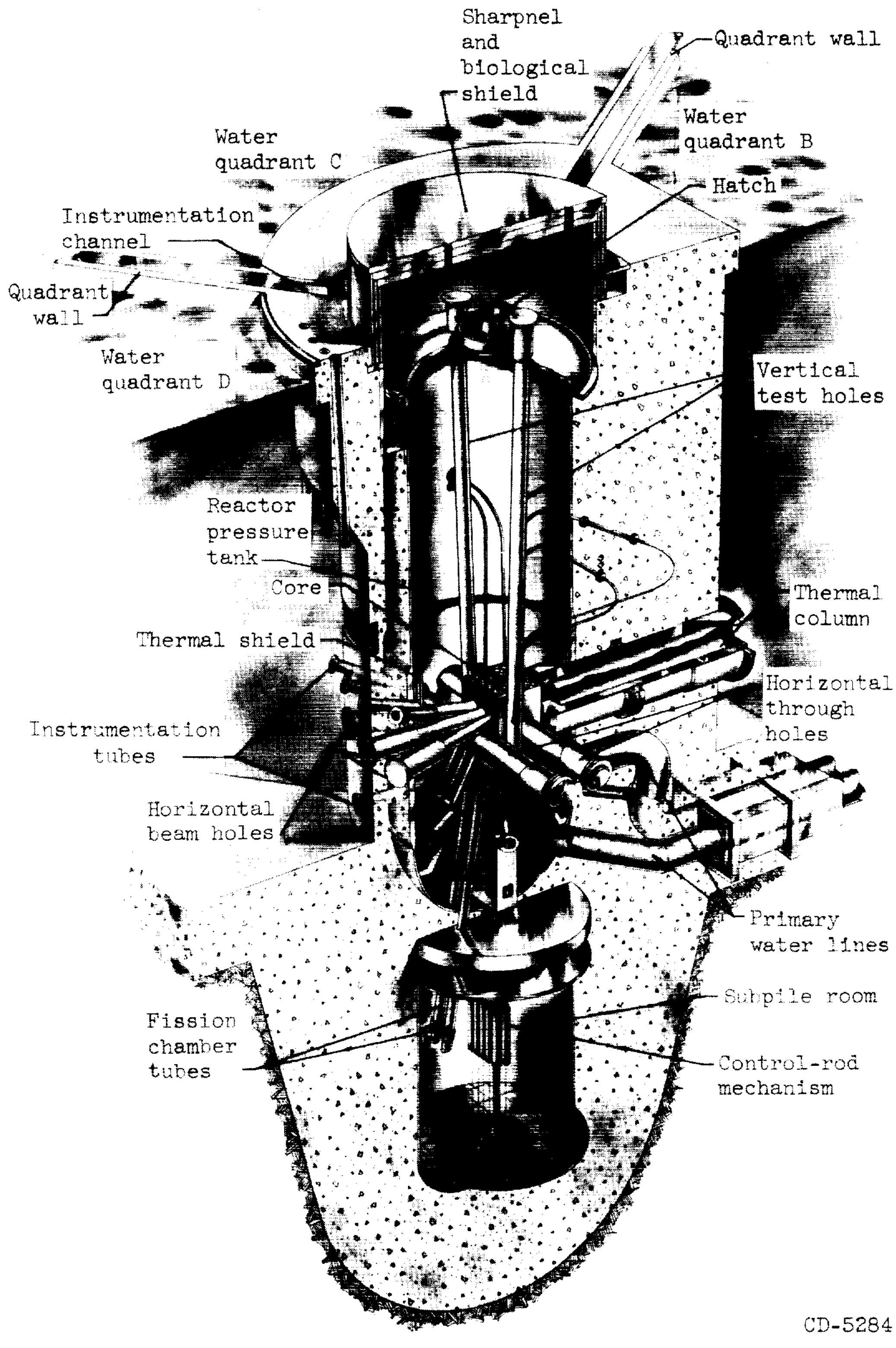
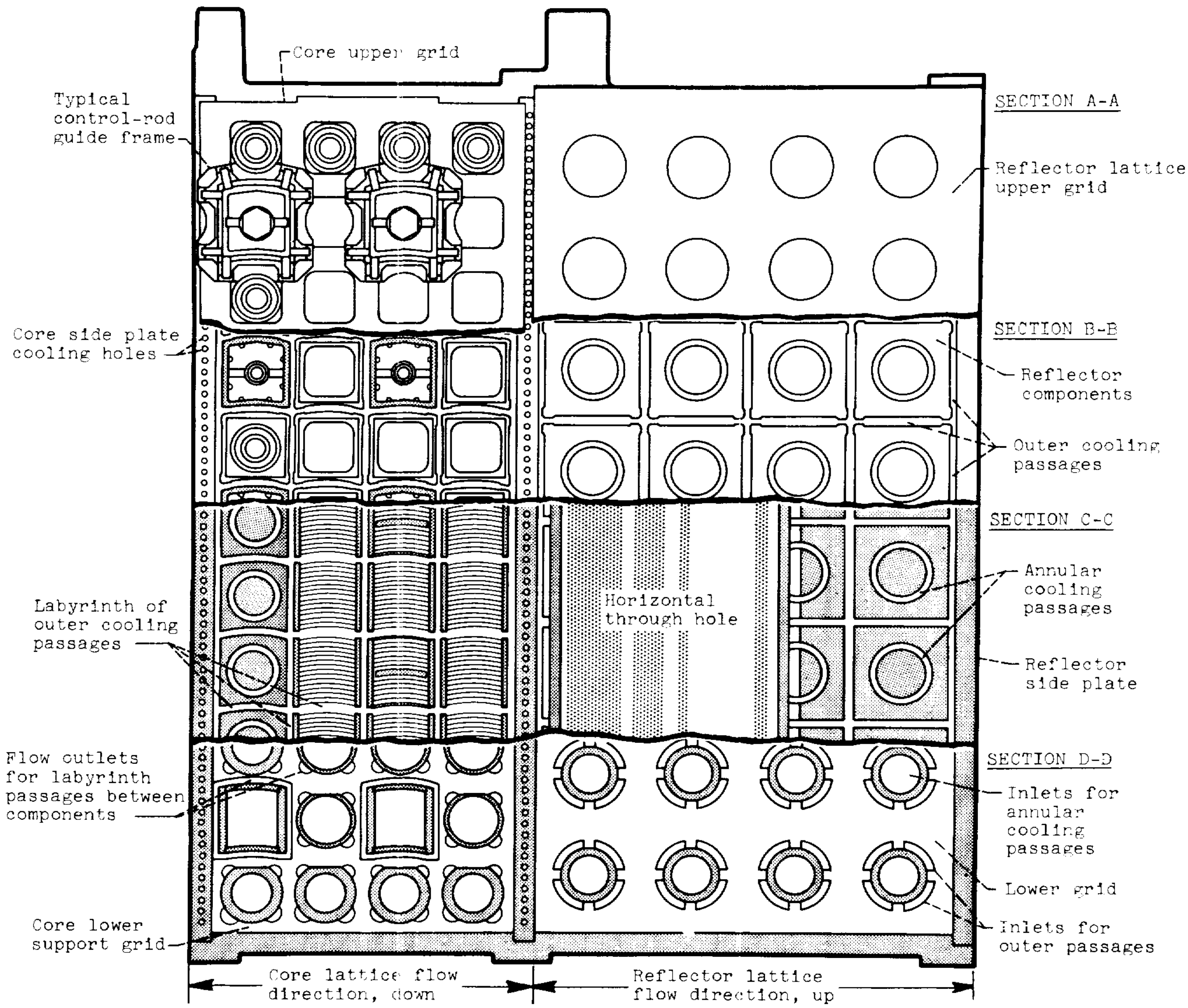
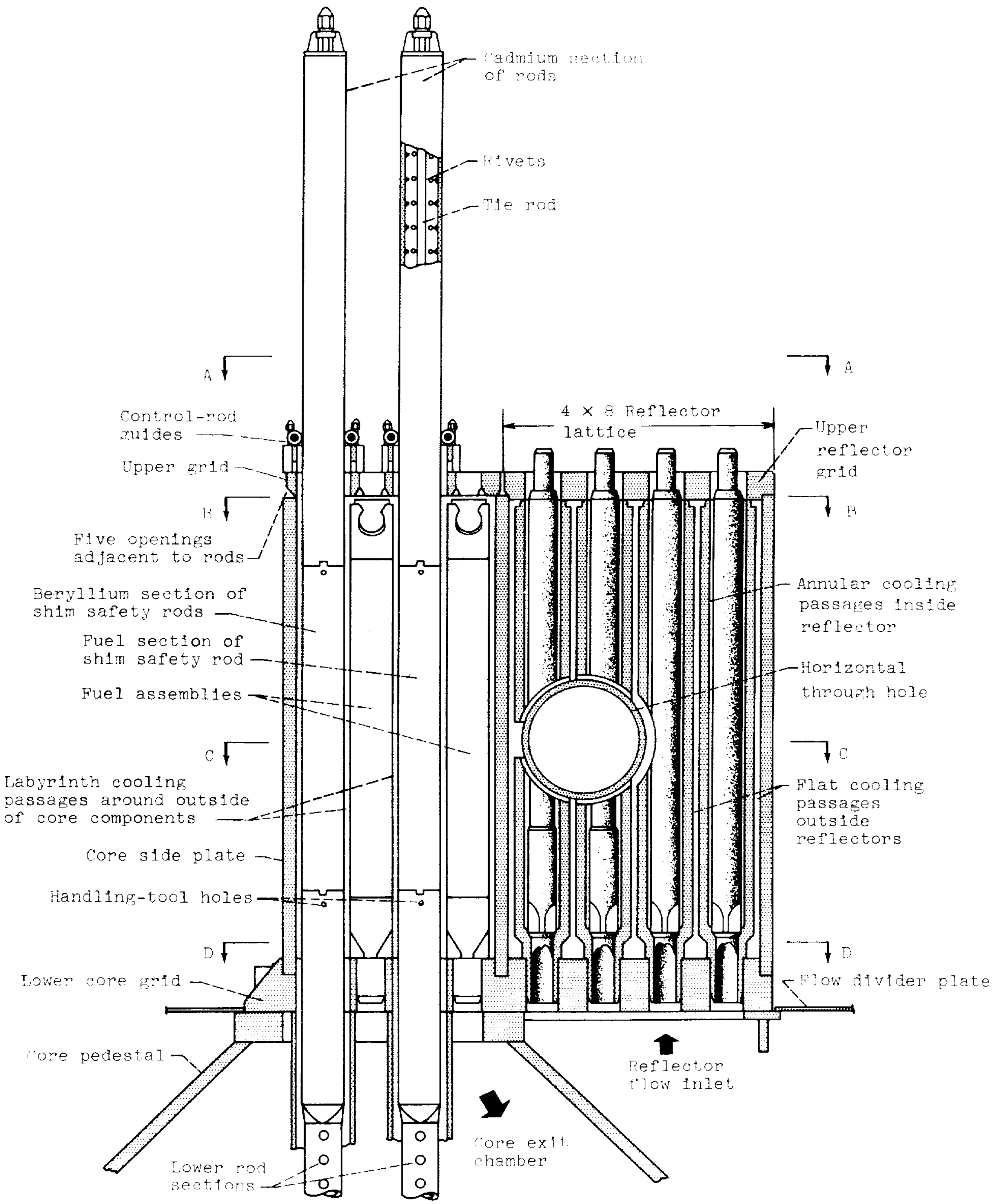


Figure I-1. - Cutaway perspective reactor tank assembly.



(a) Simplified cutaway plan view.

Figure -2. - Reactor core and reflector lattice.



(b) Simplified cutaway elevation view. Control rods fully extended.

Figure I-2. - Concluded. Reactor core and reflector lattice.

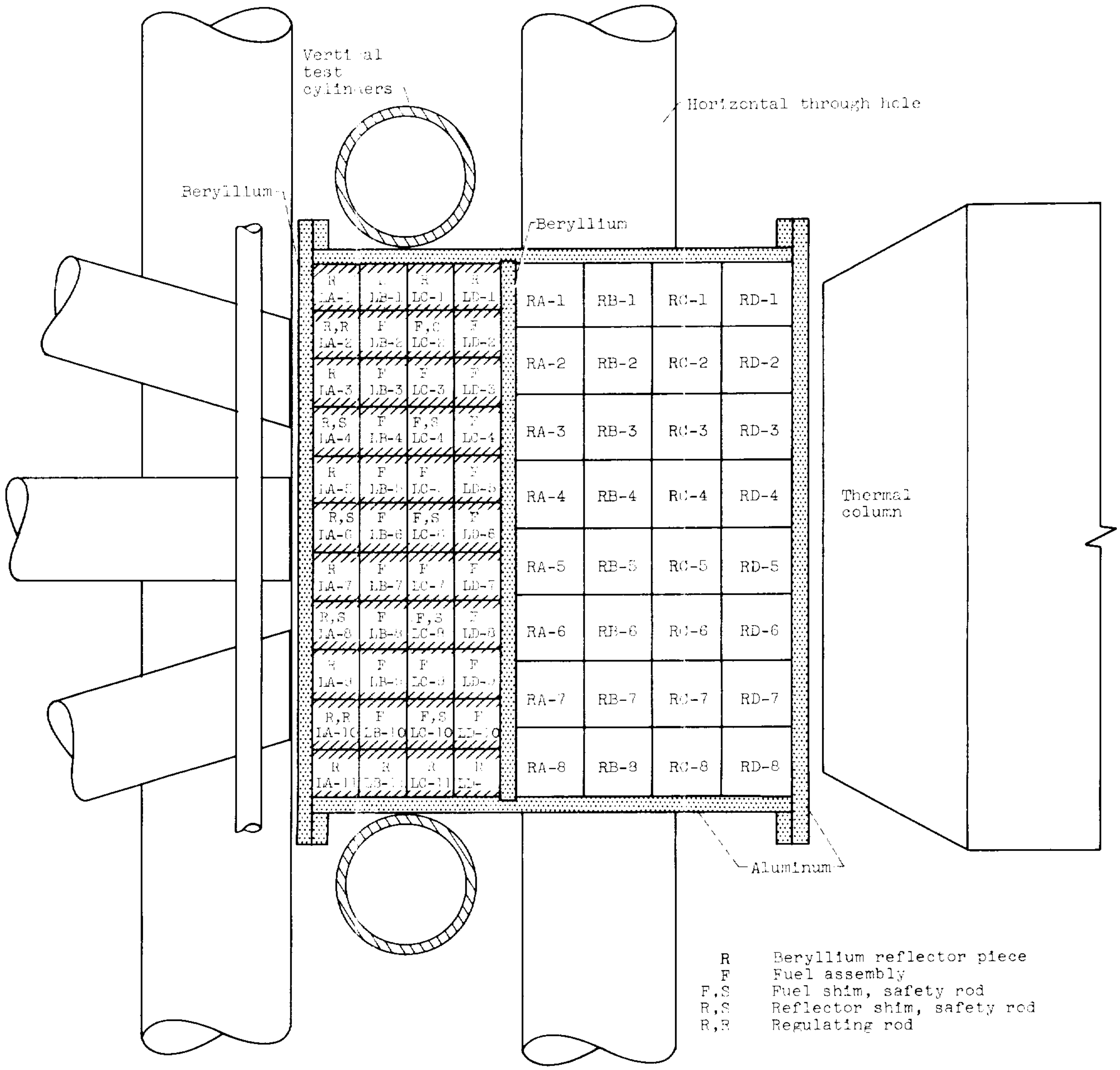


Figure I-3. - Core and reflector coordinates.

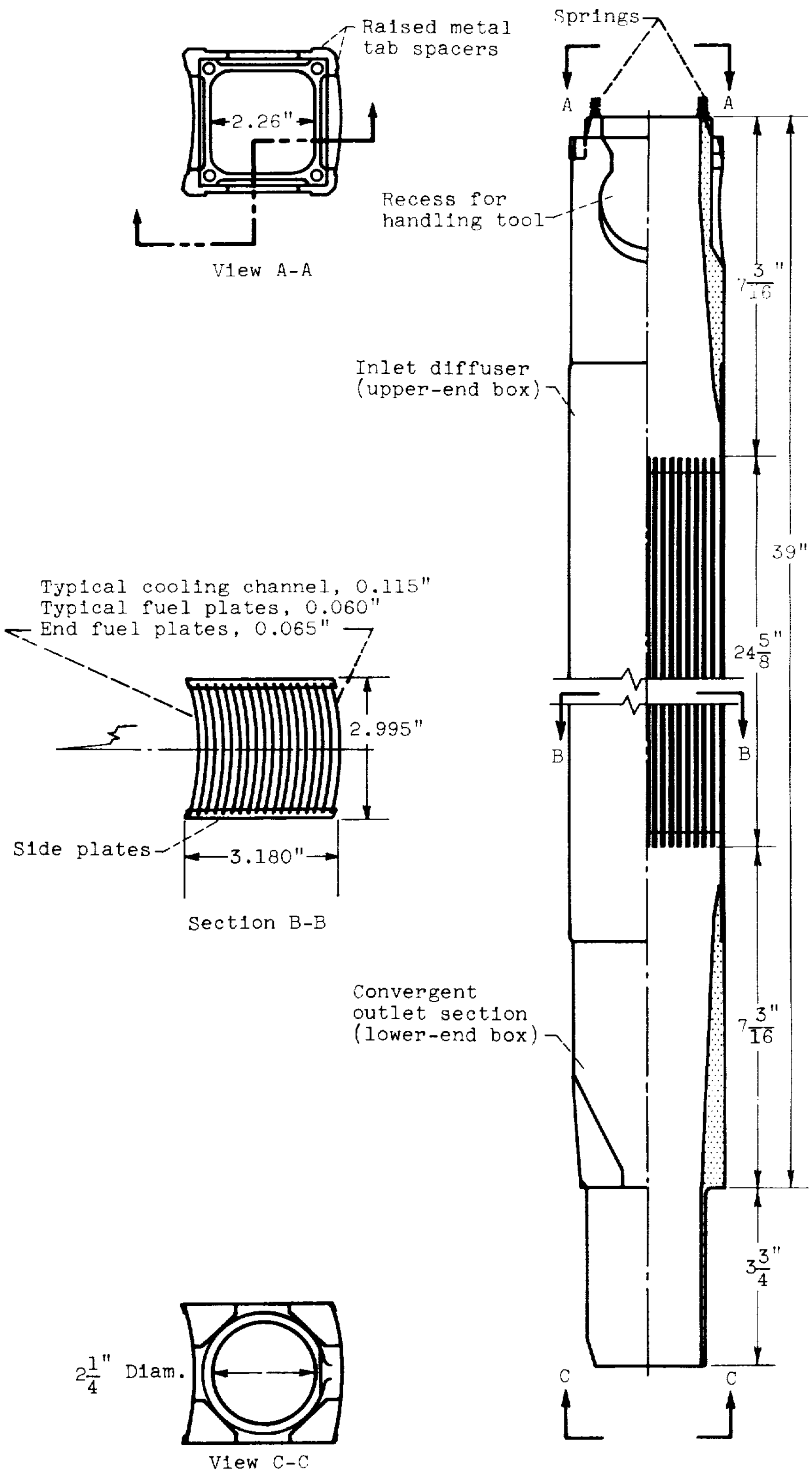


Figure I-4. - Typical NASA Plum Brook Reactor fuel assembly.

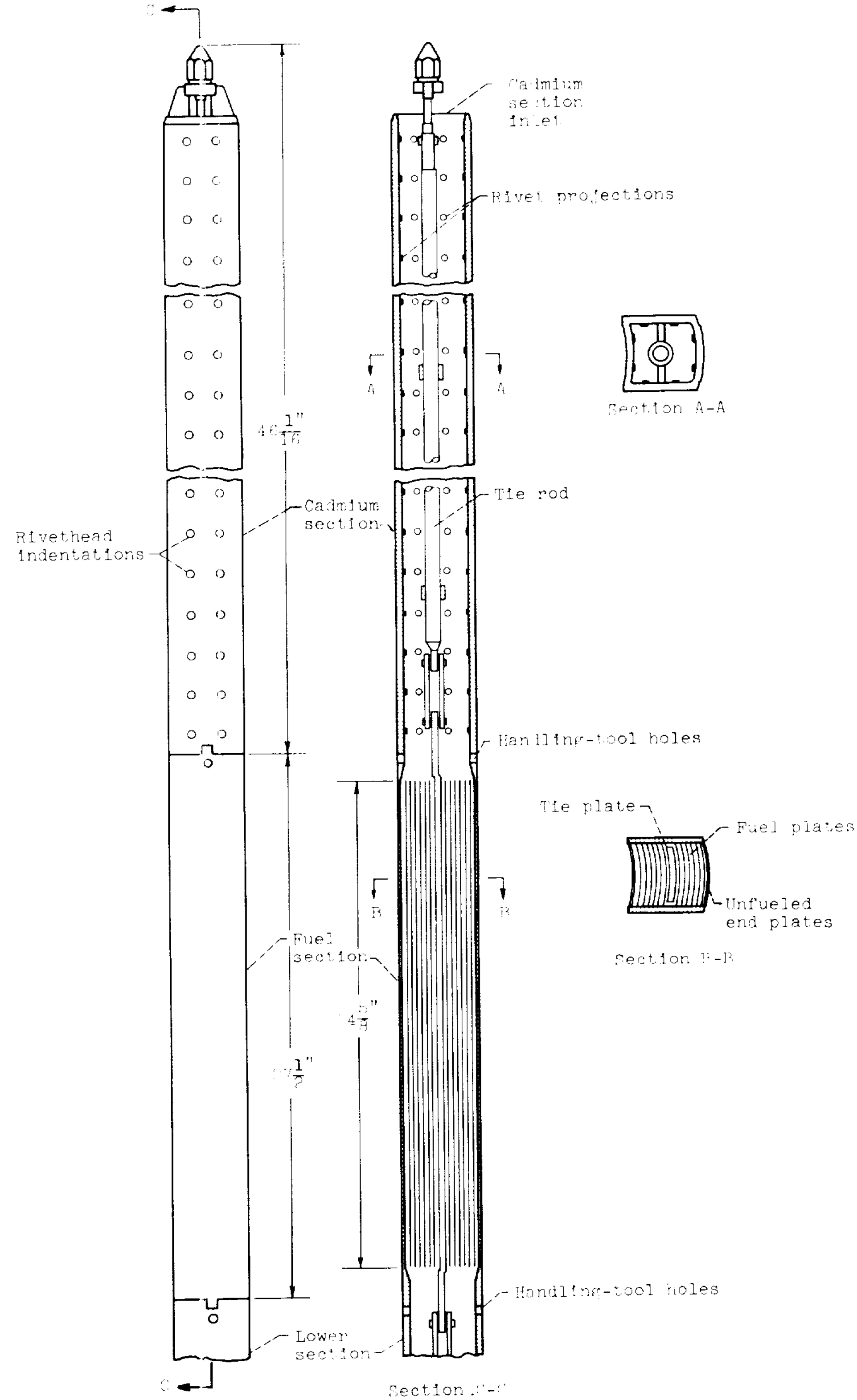


Figure I-5. - Typical NASA Plum Brook Reactor fuel shim safety rod.

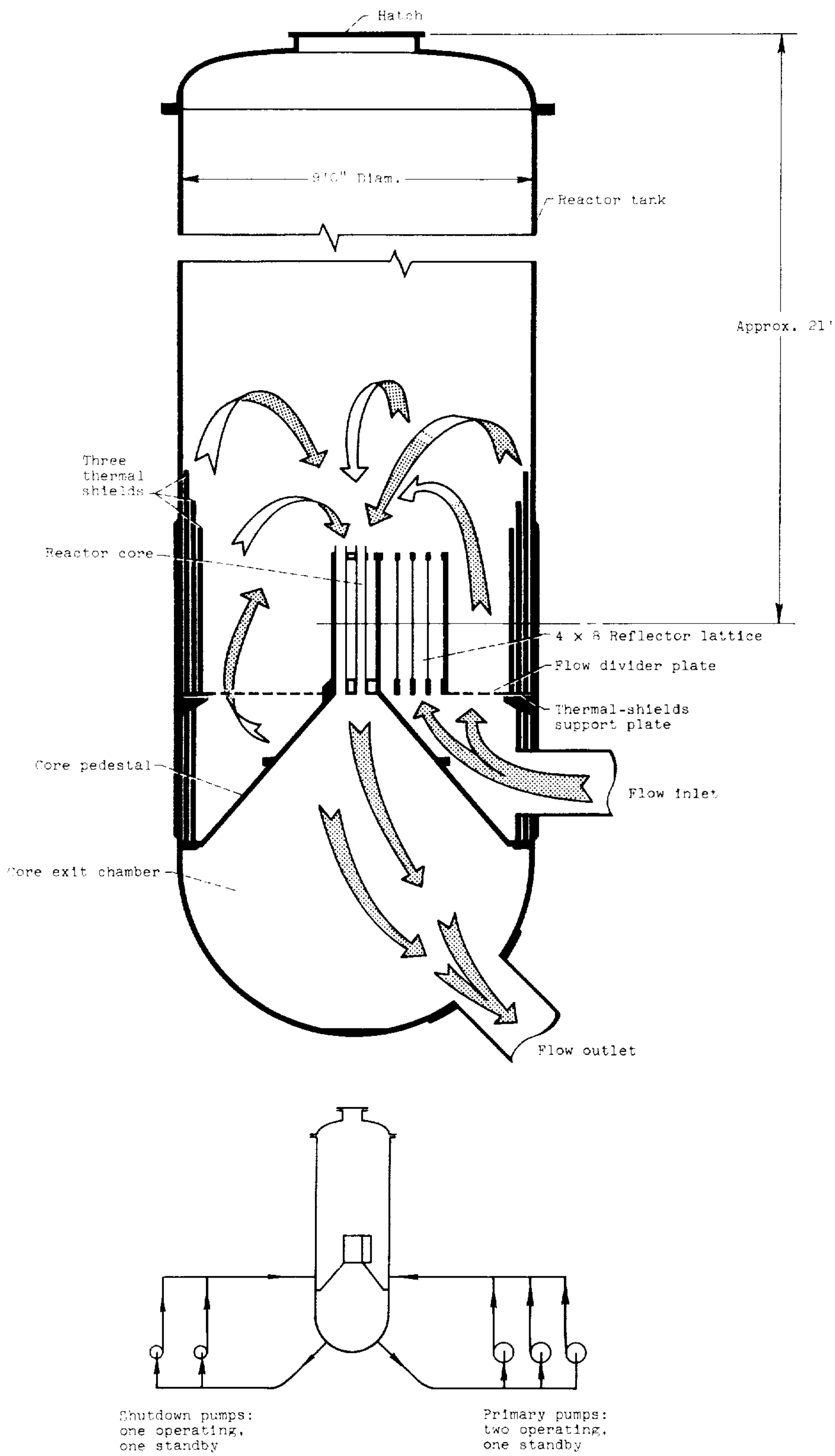


Figure I-6. - Schematic arrangement of reactor tank, components, and flow pattern.

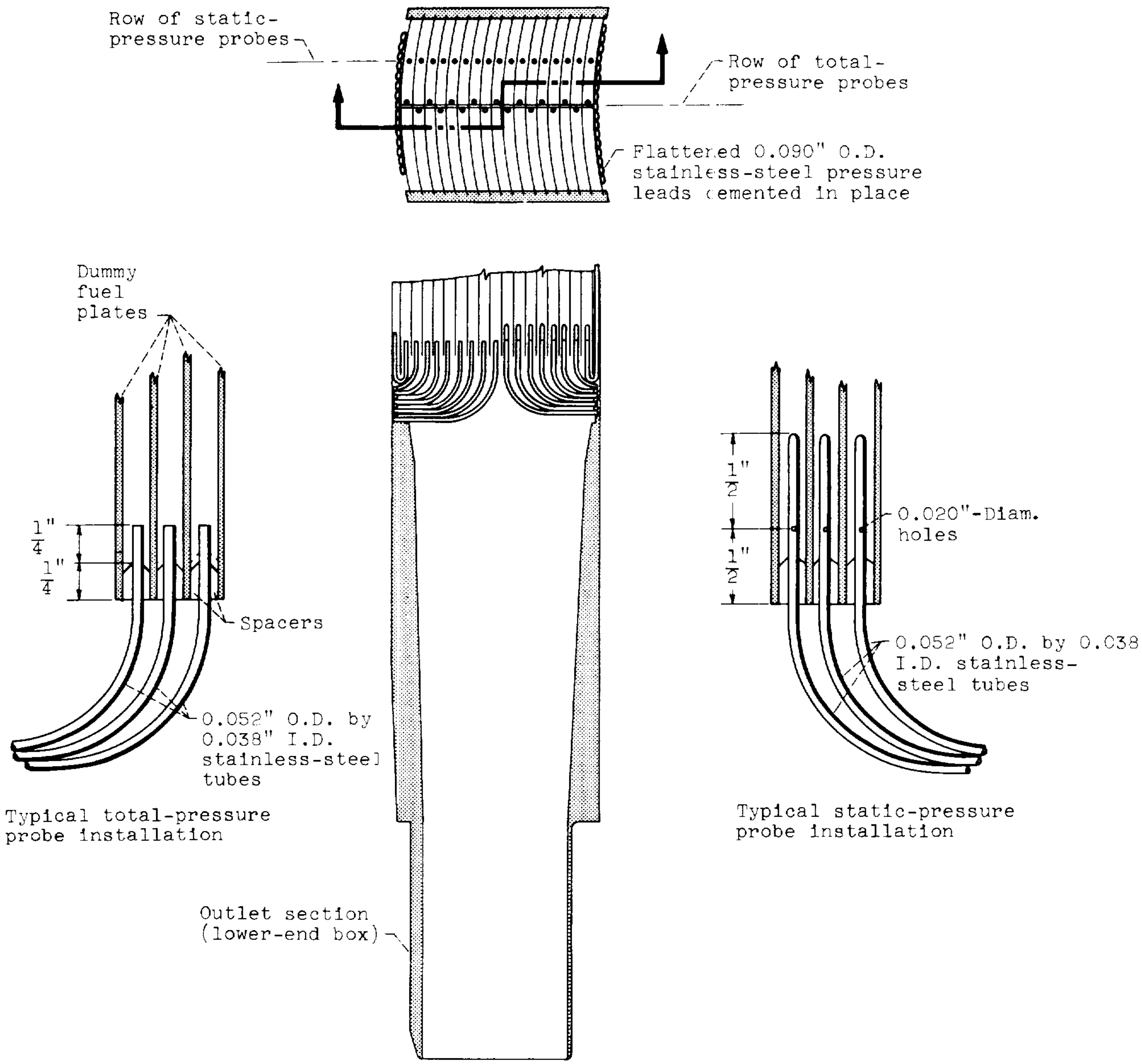


Figure I-7. - Schematic of velocity probe installation inside a dummy fuel assembly for velocity distribution measurements for tests in core.

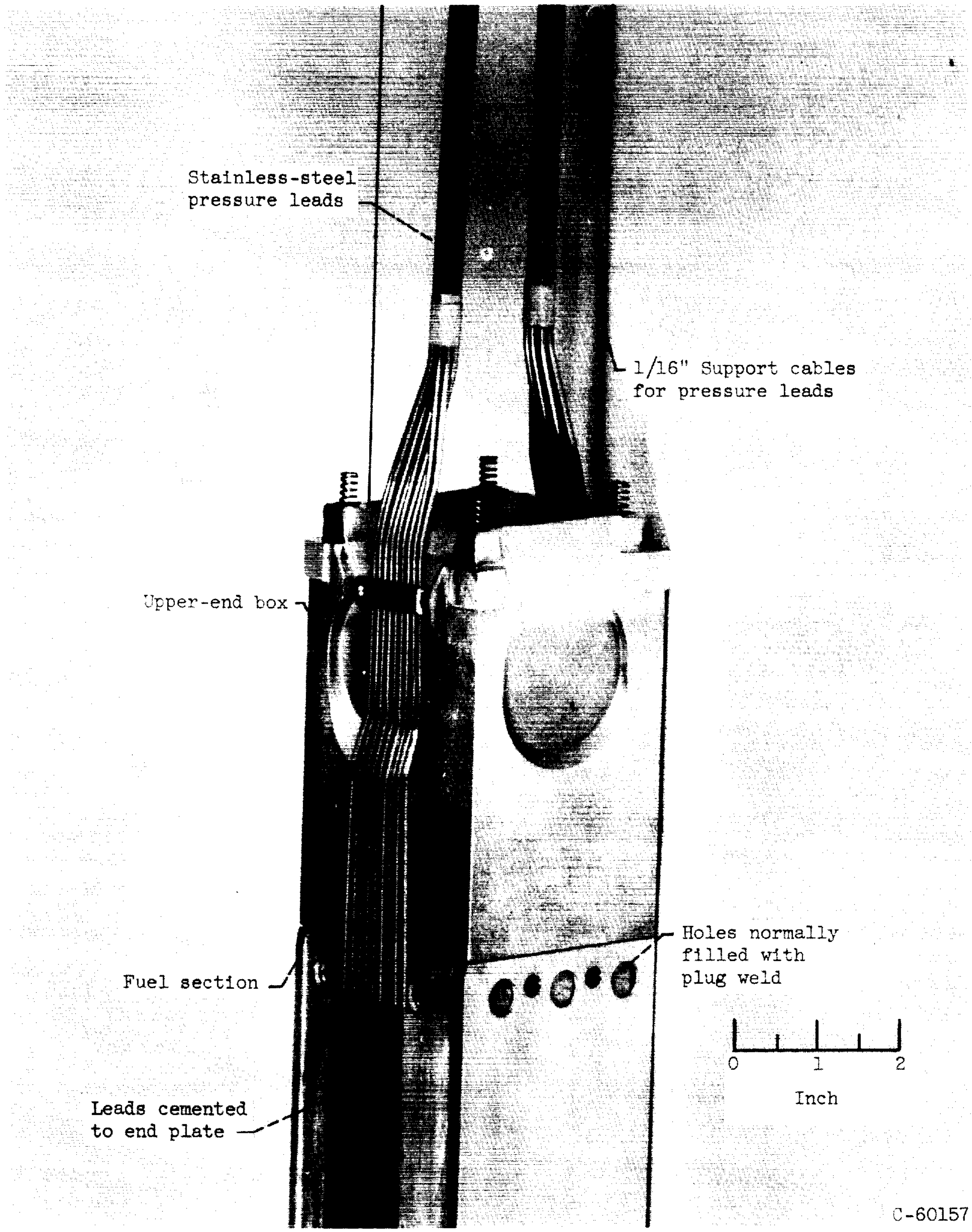


Figure I-8. - Arrangement of pressure leads at upper-end box of fuel assembly.

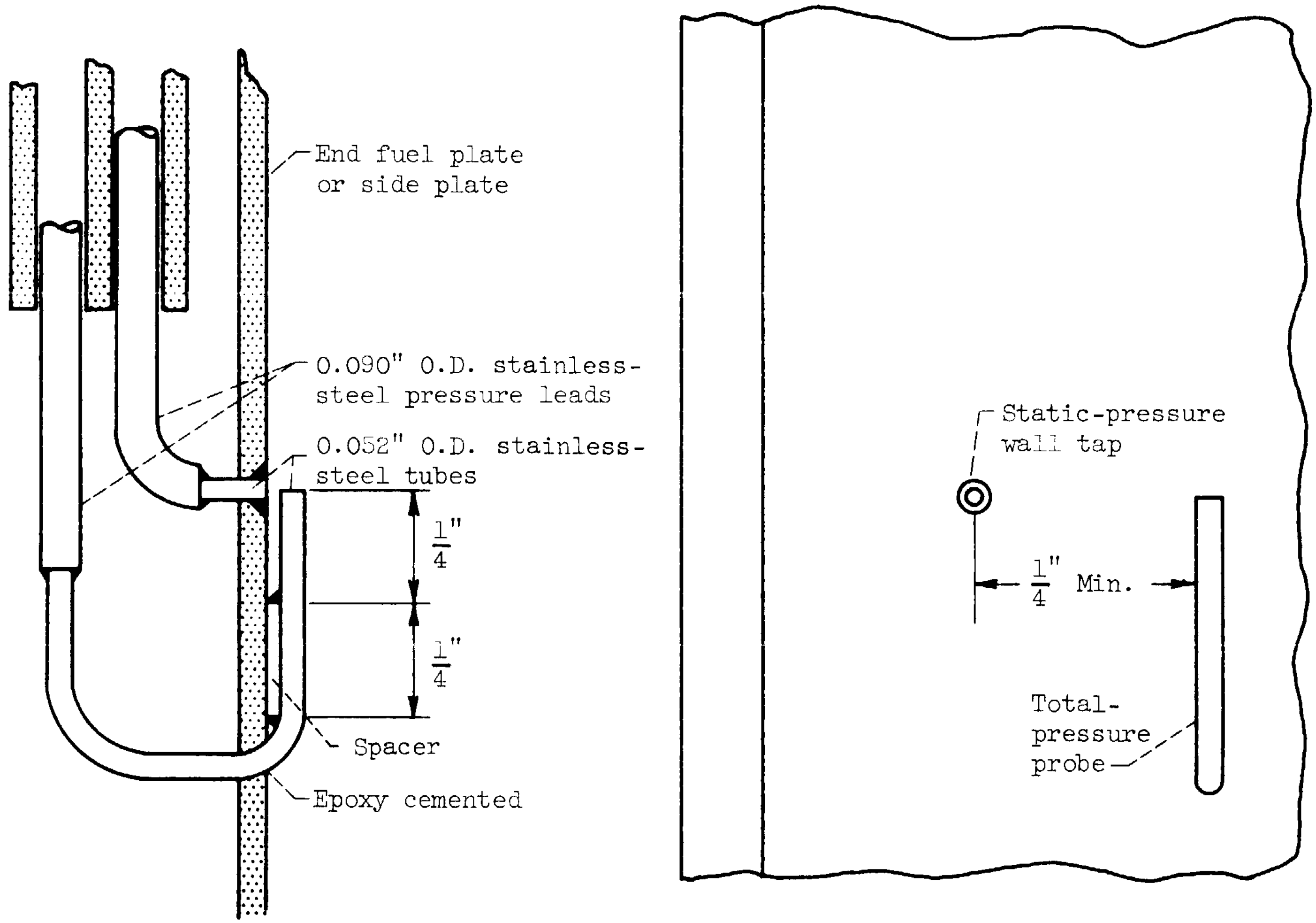


Figure I-9. - Typical total-pressure probe and static-pressure tap on outer surfaces of fuel assemblies.

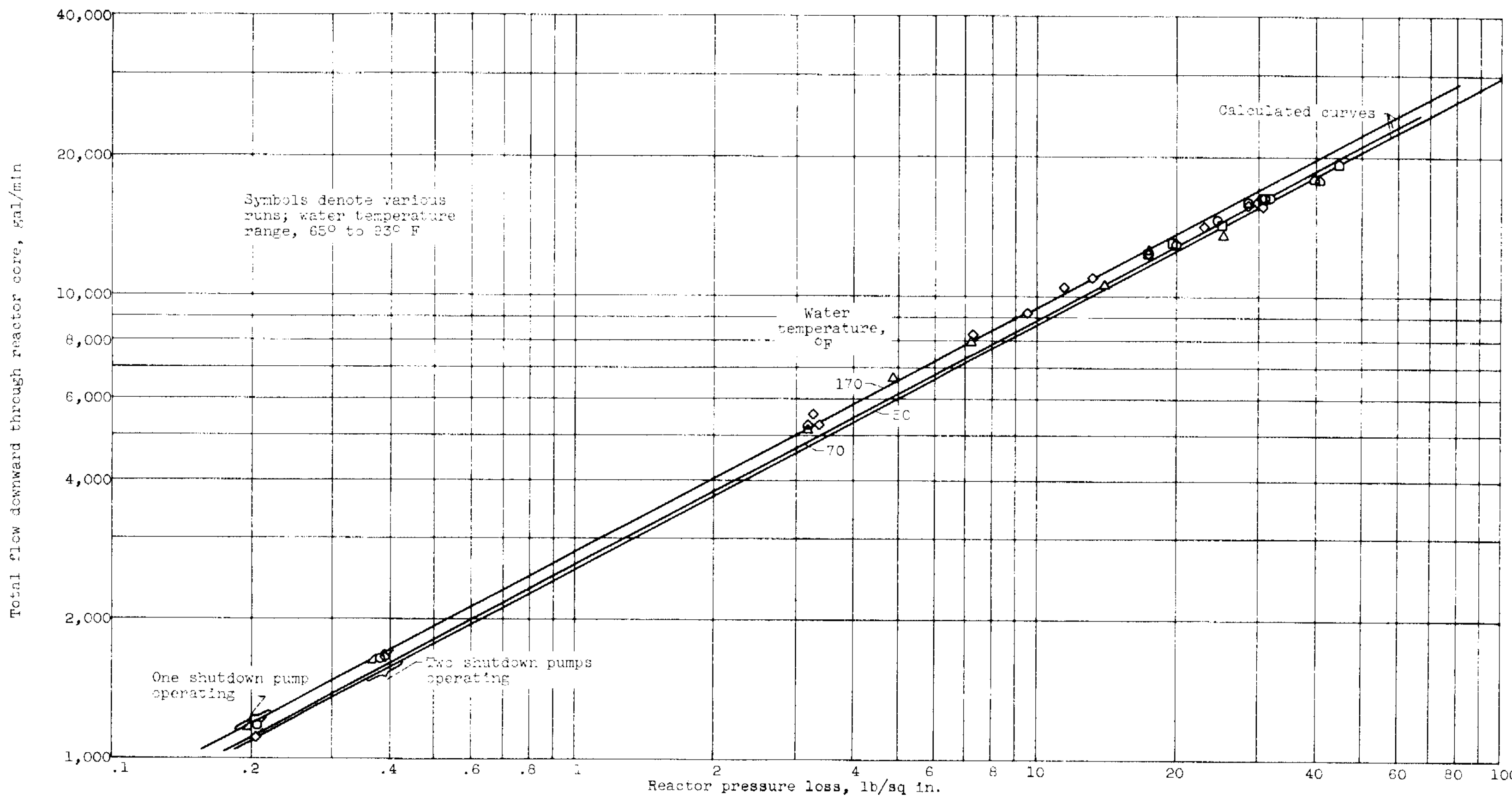
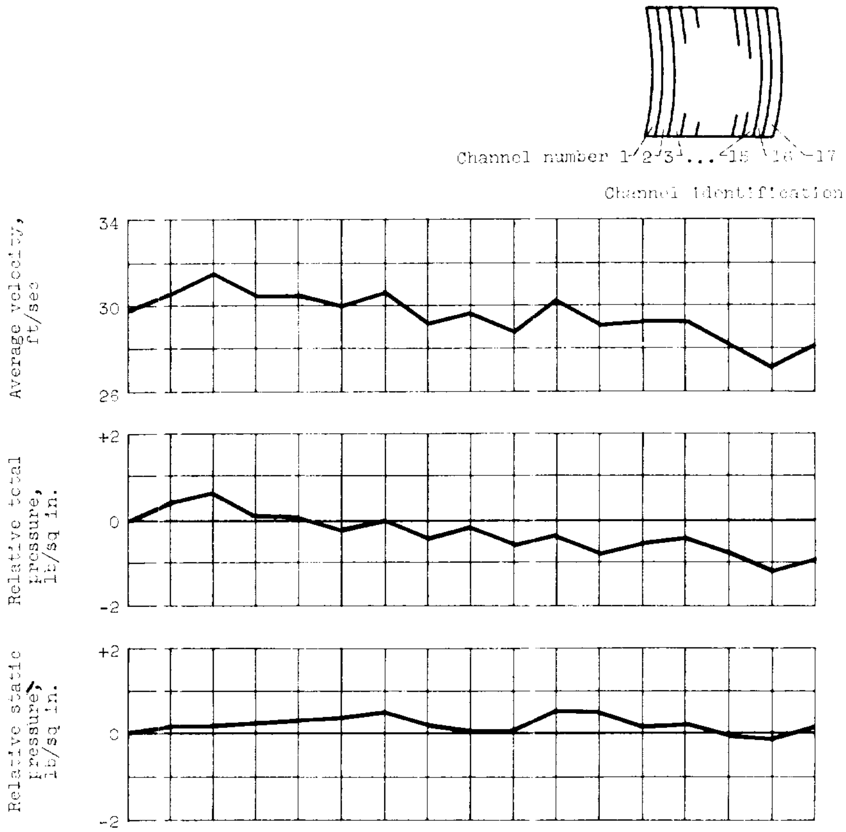
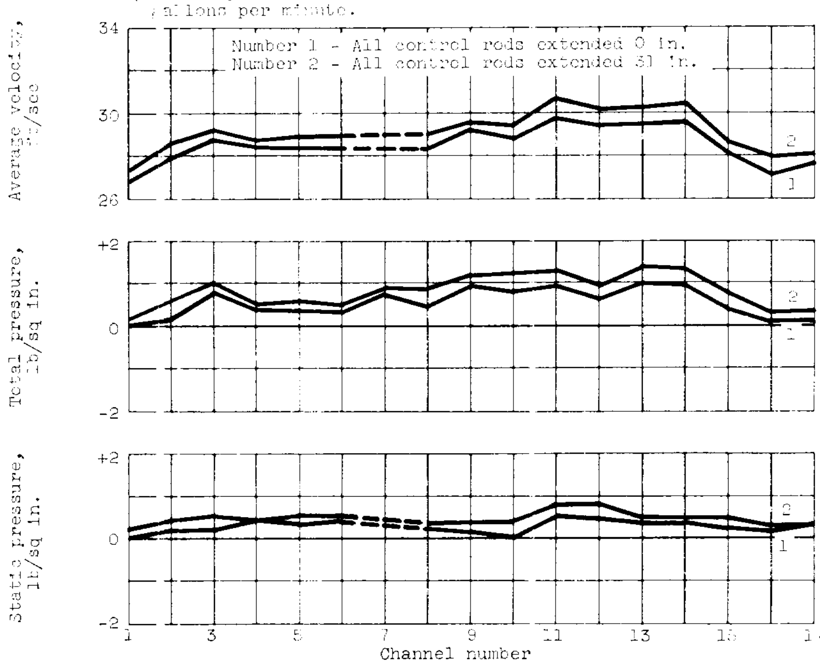


Figure I-10. - Total flow through reactor on down pass plotted against reactor pressure difference.

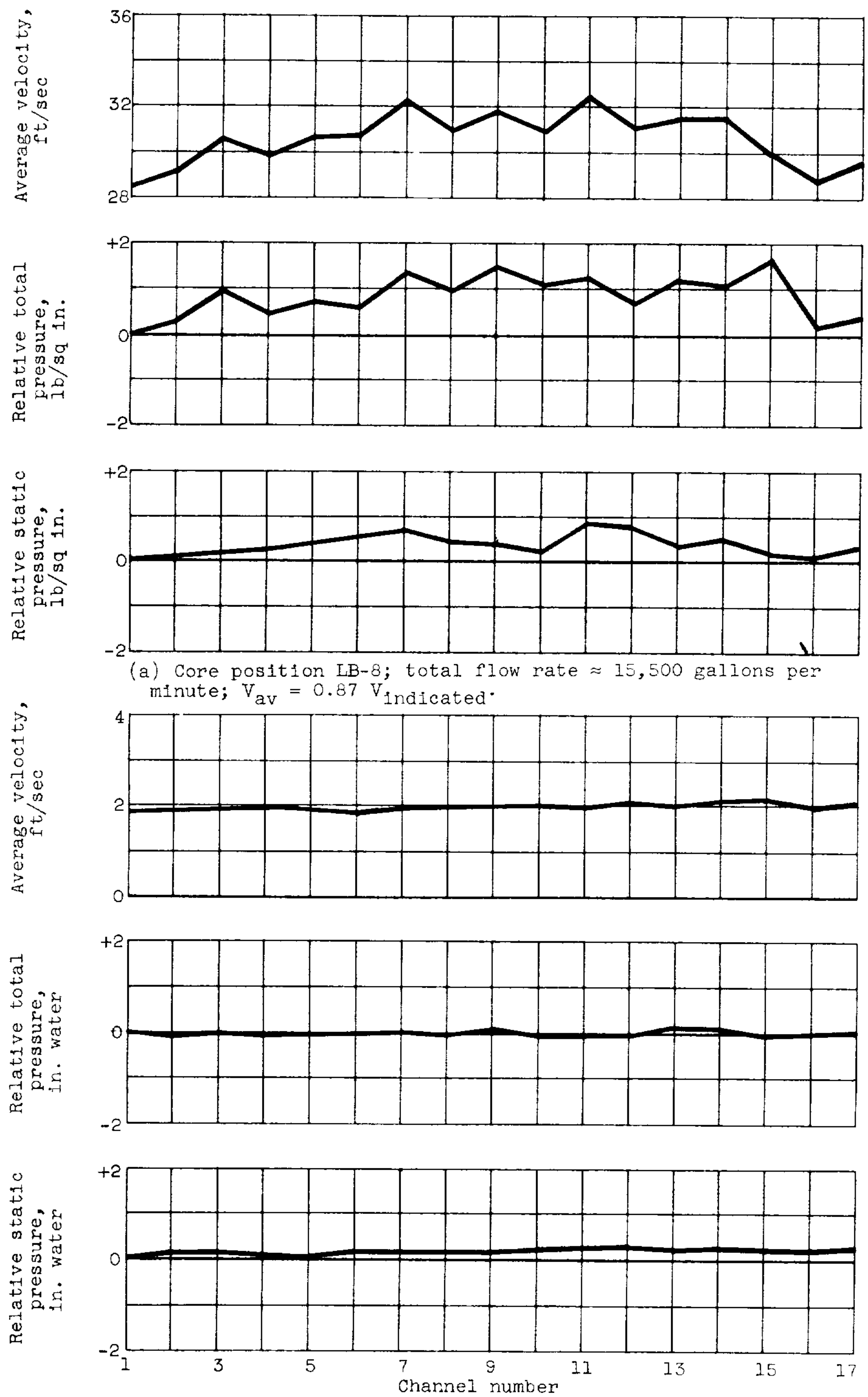


(a) Core position LB-[illegible]; total flow rate through core ≈ [illegible] gallons per minute.



(b) Core position LD-10; total flow rate through core ≈ 15,700 gallons per minute.

Figure I-11. - Velocity, relative total-, and static-pressure distribution among channels inside unmodified fuel element in core; $V_{av} = 0.[illegible] V_{Indicated}$.



(a) Core position LB-8; total flow rate ≈ 15,500 gallons per minute; $V_{av} = 0.87\ V_{indicated}$.

(b) Core position LD-7; shutdown flow rate = 1164 gallons per minute; $V_{av} = 0.75\ V_{indicated}$.

Figure I-12. - Velocity, relative total-, and static-pressure distribution among channels inside unmodified fuel element in core.

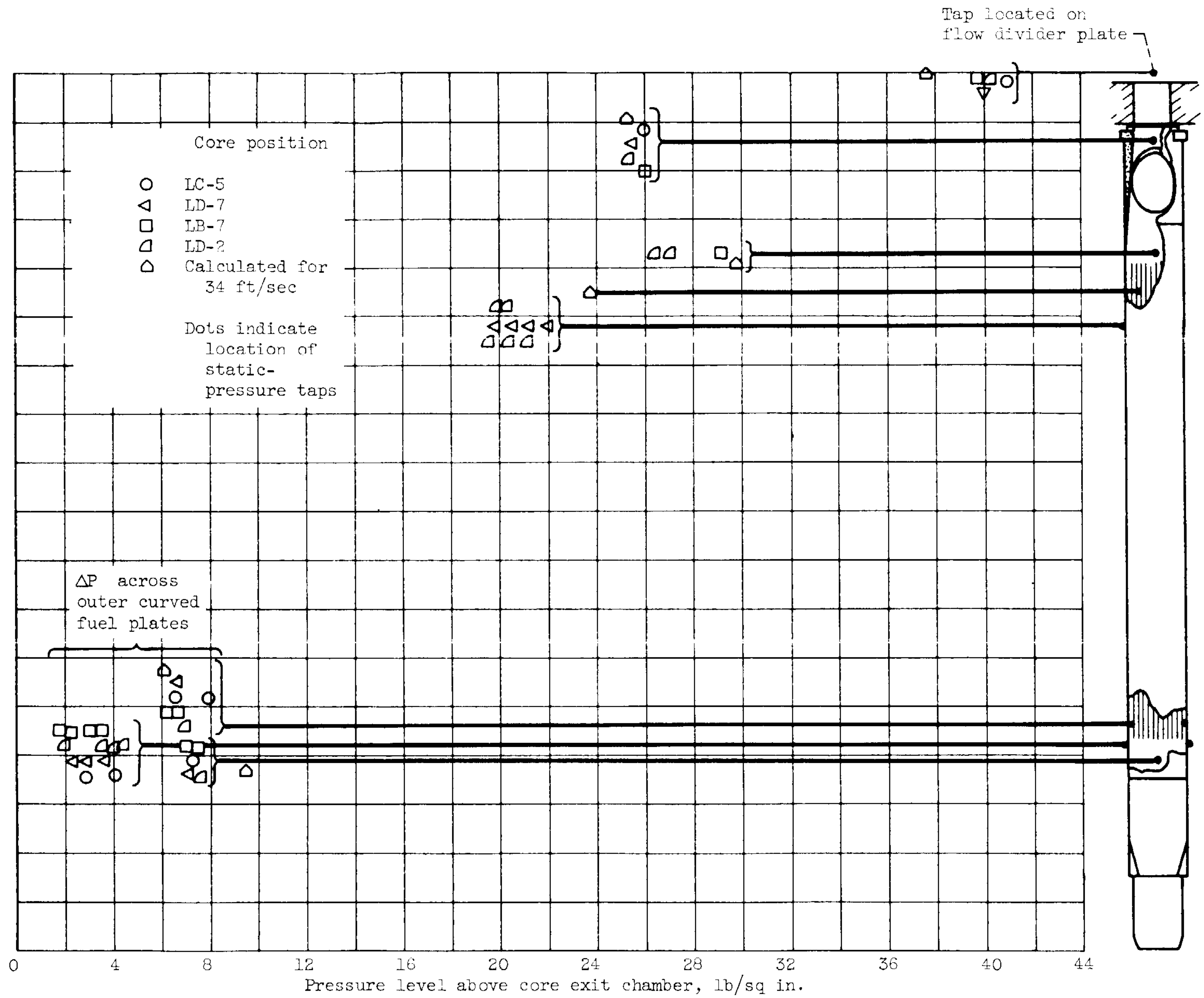


Figure I-13. - Static-pressure distribution inside and outside modified fuel assembly; total flow rate ≈ 17,700 gallons per minute.

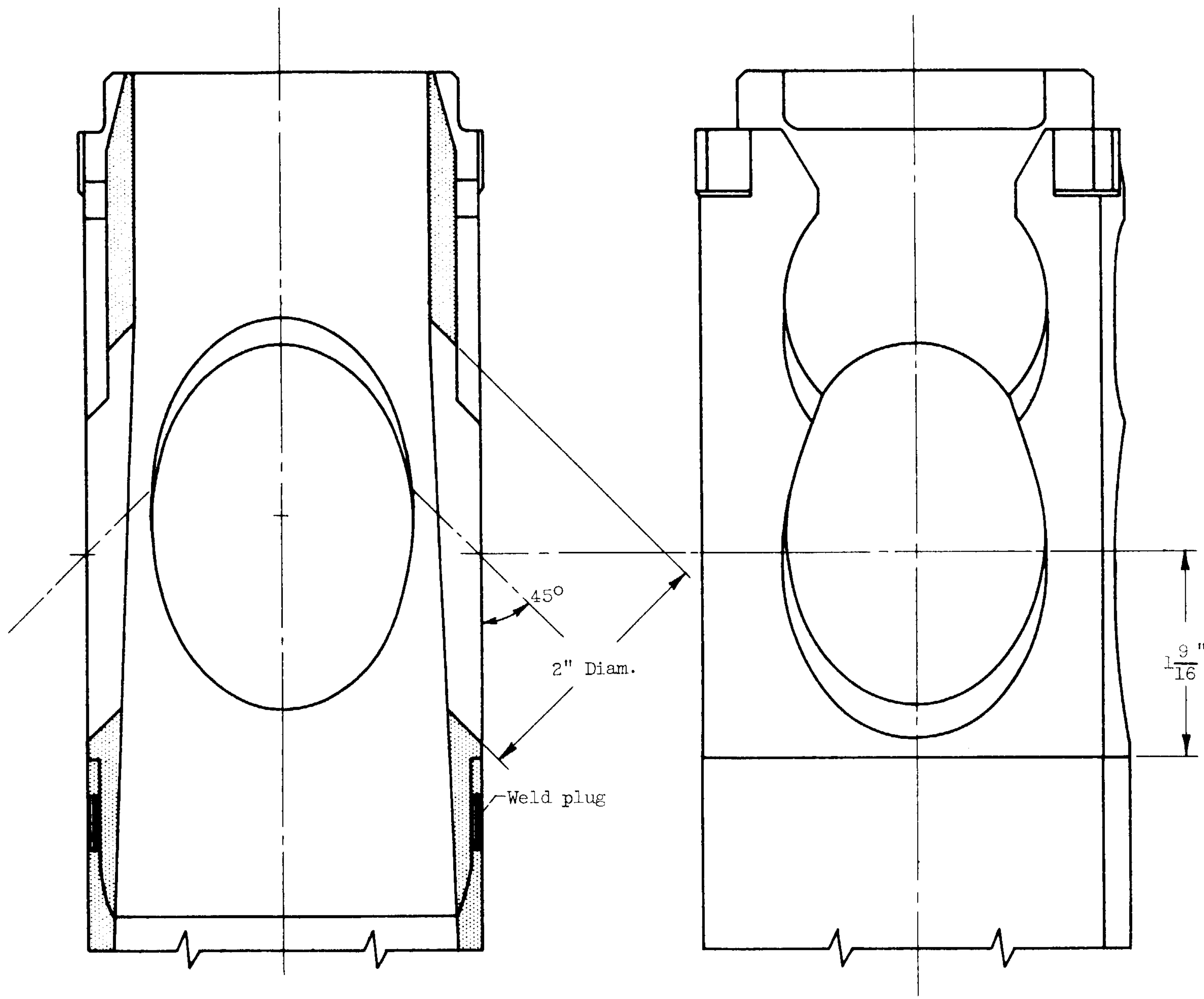
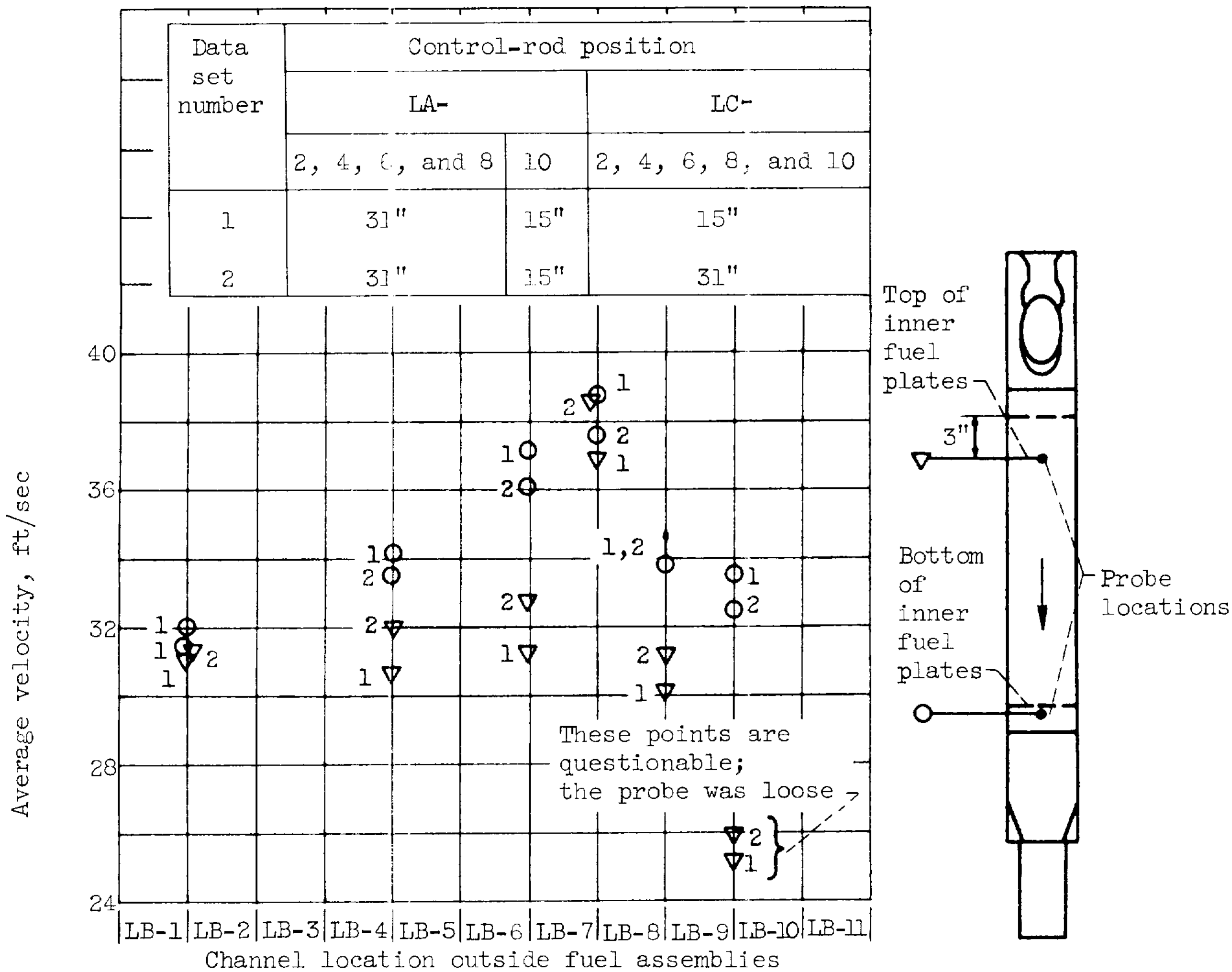


Figure I-14. - Modification of fuel-assembly upper-end box.



Data set number	Control-rod position		
	LA-		LC-
	2, 4, 6, and 8	10	2, 4, 6, 8, and 10
1	31"	15"	15"
2	31"	15"	31"

Figure I-15. - Average velocities in curved labyrinth passages outside fuel assemblies in LB row; total flow rate = 17,700 gallons per minute; $V_{av} = 0.87\ V_{indicated}$; 1 and 2 denote data set number.

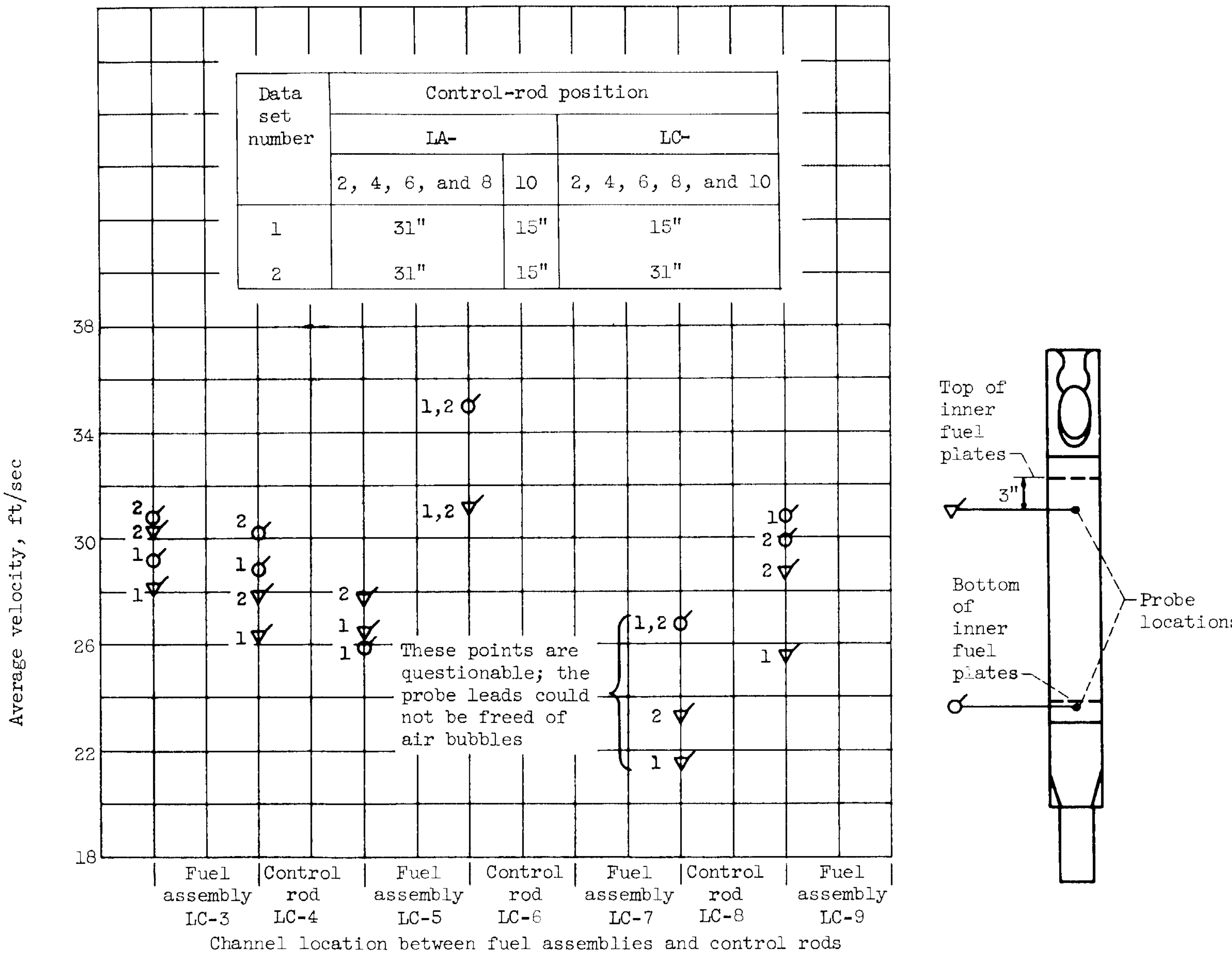


Figure I-16. - Average velocities in curved labyrinth passages between fuel assemblies and control rods in LC row; total flow rate = 17,700 gallons per minute; $V_{av} = 0.87\ V_{indicated}$; 1 and 2 denote data set number.

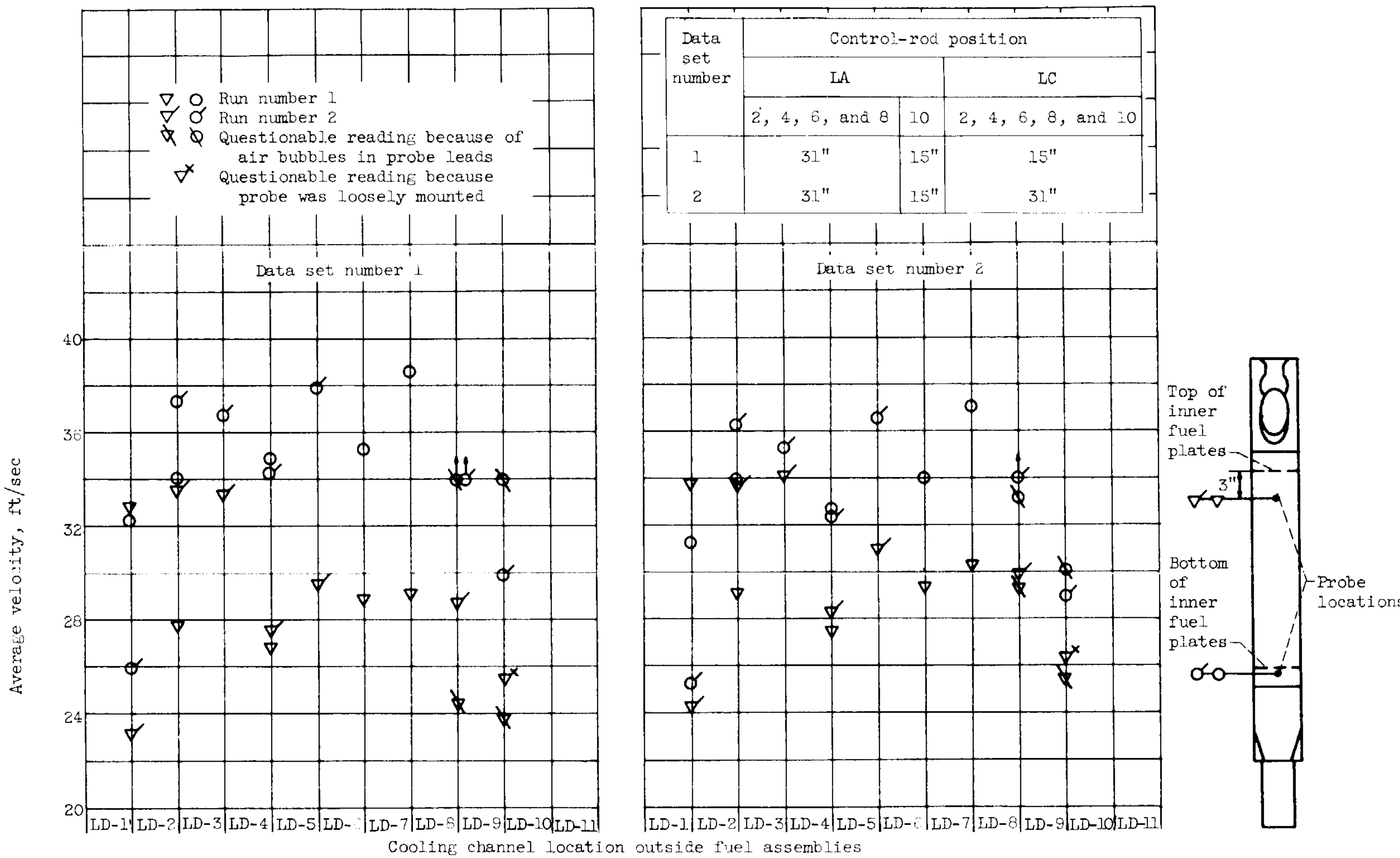


Figure I-17. - Average velocities in curved labyrinth passages outside fuel assemblies in LD row; total flow rate = 17,700 gallons per minute; $V_{av} = 0.87\ V_{indicated}$.

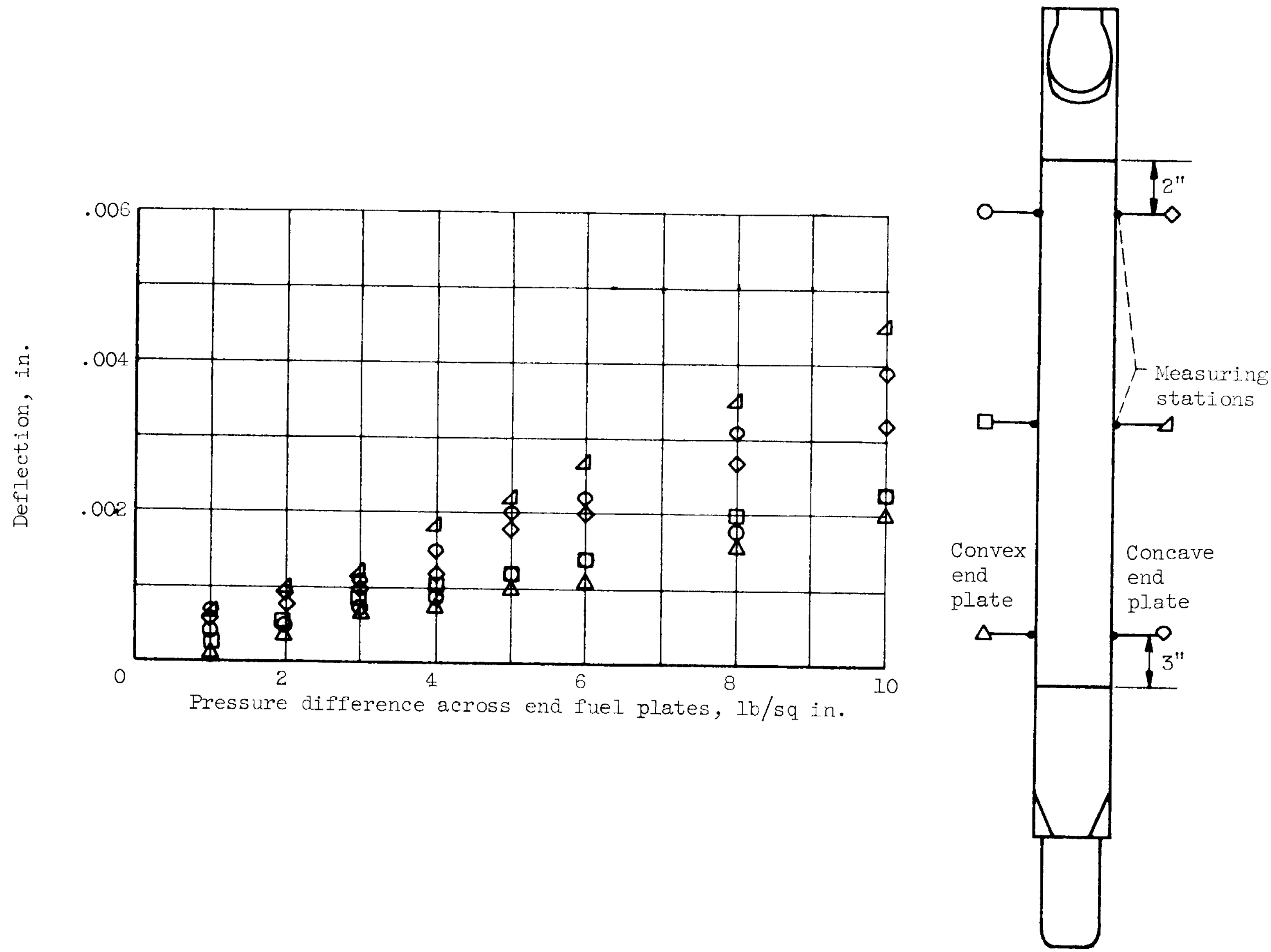


Figure I-18. - Outward deflection of end fuel plates of dummy fuel assembly due to excess internal pressure.

II - A LABORATORY STUDY OF FUEL-ASSEMBLY AND FUEL-SHIM-ROD FLOW CHARACTERISTICS

SUMMARY

A laboratory test stand capable of housing a fuel assembly or a fuel-shim rod was used to study their flow characteristics and to develop and test instrumentation to be used in the reactor flow tests. Two removable rakes, one with total-pressure tubes and one with static-pressure probes, were successfully applied to measure the velocity distribution among the fuel cooling channels inside the fuel section of a shim rod and a number of dummy fuel assemblies. These results led to the installation and testing of permanent rakes inside a fuel assembly for use in the core flow tests.

At close to design flow rates expected for full-power operation, the average velocities in the center channels of the fuel assemblies were higher by approximately 14 percent than the lowest values, which occurred in the outermost channels adjacent to the end fuel plates. The measured overall pressure loss against the flow rate through the fuel assemblies agreed very well with the calculated design values.

Because the long cadmium section smoothed any flow entrance effects before the water arrived at the fuel-section inlet, the fuel-section flow characteristics measured in the laboratory also applied when the rod was in the core. This simplified the tests within the core. The velocity distributions measured inside the fuel section of the shim rod with special rakes were sufficiently uniform to satisfy the design specifications. The pressure loss from inlet to outlet of the shim-rod fuel section was calibrated against the flow rate through it for use in the core flow tests. In this way the bulk flow rate through the inside of the rod could be accurately determined when the rod is in the core by measuring the fuel-section pressure loss. Thus, the laboratory tests were a very useful part in the overall core flow test program.

INTRODUCTION

An indispensible part of any nuclear-reactor flow testing program is a laboratory study of the important reactor components such as the fuel assemblies and shim rods. Much information about the flow properties of these components and the instrumentation can be acquired that is very useful to the core tests. For example, the laboratory data are valuable as a basis for comparing the results of the reactor tests. Also, these tests provide the opportunity for developing and testing the instrumentation prior to its use in the core, which avoids difficulties and costly delays. Often a foreknowledge of a flow discrepancy in the core is obtained from the laboratory studies. Thus, the experience gained from the laboratory experiments can contribute significantly to the success of the flow tests in the reactor.

Curved-plate fuel assemblies are one of the more common types used in nuclear reactors, and, as a consequence, information is available on their flow properties and the instrumentation used to measure the properties. A single-assembly flow loop is used in reference 1 to measure the overall pressure loss against flow-rate characteristics and the velocity distribution among five of the 19 fuel cooling passages of the ORR fuel assemblies. The ORR fuel assemblies are a curved-plate type very similar in construction to the PBR assemblies. Stainless-steel probes 0.080 inch in outer diameter were used to measure the total and static pressures in the fuel cooling channels. The velocities in the central channels were found to be about 17 percent higher than those in the channels that cool the inner surface of the end fuel plates.

Reference 2 reports the velocity distributions among the cooling channels of a typical curved-plate MTR fuel assembly where the velocities were calculated from the measured friction pressure loss in each channel. These tests were conducted in a single-assembly laboratory flow loop. The velocities were found to be about 14 percent higher in the central channels than those next to the end plates. Also discussed are some preliminary results on the use of pitot and static tubes for measuring velocities in the fuel cooling channels but later (ref. 3) discards this method in favor of the former. In reference 4 (p. 18), similar results are given for velocity distribution tests on the flat plate SPERT III type-C fuel assembly, where the center channels had the higher velocities. The velocities in the flat plate SPERT IV type-D assemblies were fairly uniform except for the channels adjacent the end plates (ref. 5, p. 18). The ETR flat-plate-type fuel assemblies were studied extensively (ref. 6) in flow loops that could house one or more assemblies. The purpose of the tests was to improve the flow and pressure distributions inside the assemblies so they could operate at design flow without buckling. Two methods were used to measure velocities in the fuel cooling channels: (1) the friction loss technique mentioned previously, and (2) a velocity and static-probe technique, which was invalidly applied. All these reports and others not referenced illustrate the value of laboratory testing each new type of fuel assembly and shim-fuel rod. Except for reference 1, there are no reports on the use of a pitot-type velocity probe inside fuel assemblies. The purpose of part II is to present details on the methods that were developed to measure individually the flow characteristics of two dummy shim-fuel-safety rods and a group of dummy fuel assemblies and to give some of the laboratory test results.

DESCRIPTION OF APPARATUS

The main test section housing and inlet calming chamber of the laboratory flow loop are shown in figure II-1. Water from a 10,000-gallon open pool was drawn into a 30-horsepower centrifugal pump having a maximum capacity of 500 gallons per minute and was discharged through a globe-type throttling flow control valve. The water then passed through a horizontal run of pipe containing a venturi meter in series with a turbine flowmeter, through a vertical length followed by a horizontal length to the top of the test section calming chamber. The screens and perforated pipe served to disperse the stream entering the 6-inch calming chamber. The chamber was made sufficiently long to accommodate a control rod. In an attempt to duplicate conditions in the core, the inlet to the fuel-assembly housing was fitted with three removable pieces: one simulating the upper grid and two simulating the portions of the control-rod guide frames that hang over the grid hole above the assembly. A bellmouth entrance piece to the grid was also used to assess the influence of the flow profile entering the grid on the flow characteristics of the fuel assemblies. No provisions were made to permit water flow around the outside of the assembly on the control rod. Hence, the pressure in the spaces between the assembly and the housing was approximately equal to that at the top of the assembly. The calming chamber was fitted with means for bringing out pressure leads of the instrument assemblies and the rod that were to be used in the core.

The only instrumentation on the test section was the static-pressure taps shown in figure II-1. The difference between the static pressure measurement made by the tap on the calming chamber 6 inches above the housing flange and the atmospheric pressure was used as the overall pressure loss through the fuel assemblies.

The typical dummy fuel assemblies and two fuel-shim-safety rods with a dummy fuel section that were tested are shown in figures I-4 and I-5. Six assemblies were built with removable inlet diffuser and outlet convergent sections that were fastened to the fuel section with screws. A special lower section was used to permit installation of the fuel-shim-safety rods into the testing stand. Also tested was the instrumented assembly to be used in the core (figs. I-7 and I-8) and the simulated fuel assemblies (part III).

The velocity distributions among the cooling channels of the fuel section of the assemblies and of one rod were measured with total- and static-pressure probes of the removable and built-in types. The theory underlying their use is presented in part I. Two removable rakes, one containing total-pressure probes and the other static-pressure probes, were constructed to fit inside the outlet convergent section of the assemblies indicated in figure II-2. A similar set of removable rakes (not shown) was fabricated to fit in the lower adaptor section of the rod. Only one removable rake at a time could be used in the assemblies because of space limitations; whereas, both removable rakes were installed in the rod. Hence, to measure the velocities in fuel assemblies with the removable rakes, a run had to be made with each rake at identical bulk flow rates. This was not necessary in some runs using built-in probes. In the removable rakes the probe pressure leads were connected to larger diameter tubing downstream of the housing outlet. The overall fuel-assembly pressure losses, the total and static pressures of the velocities' measurements, and the venturi water pressure difference were measured on a system of glass manometers having water on mercury as the working fluids. The manometer tubes were 100 inches long, and the scales were readable to 0.1 inch. Each pressure tap or probe was connected to a manometer tube with a length of plastic tubing having at least a 3/32-inch inside diameter.

The bulk flow rates through the loop were measured with the venturi and the turbine meter. Each instrument measured the flow to within 1 percent. The output of the turbine meter was read out on a pulse rate counter and a strip-chart recorder.

TEST PROCEDURE

Each test was started by readying the component to be tested. For measurements of the velocity and static-pressure distribution among the plate cooling channels of the assemblies and the rod, one of the removable probe rakes was mounted in position prior to installation of the component in the housing. For overall pressure loss data, the assemblies and the rod did not require any special preparations prior to placing them in the loop. All the pressure leads from the assembly or rod being tested were then connected to the manometer tubes. After all instrumentation had been readied, the flow was started and set at the maximum value near 500 gallons per minute. The air bubbles were then bled from all the pressure lead lines. All the test data were recorded after the mercury-water interface in the manometers and the flow rate had reached constant values. The bulk flow rate through the loop was then reduced, and the data were recorded after all conditions again reached equilibrium. This procedure was repeated until all the desired measurements had been made.

Various test conditions were investigated in addition to the range of flow rates. The inlet to the simulated upper grid piece was fitted, in different tests, with either the bellmouth or simulated control-rod guide overhangs, or neither, to assess their influence on the flow characteristics of the fuel assemblies. The tests were conducted at water temperatures in the range of 55° to 70° F.

DATA PROCESSING

As in part I, most of the data processing was straightforward except for the velocities measured with the probes. The method used to assess the average velocity in a channel from the indicated probe readings is discussed in part I.

RESULTS AND DISCUSSION

Many tests were performed on the fuel assemblies, most of which were to perfect the instrumentation and experimental techniques. Figures II-3, II-4, and II-5 show representative results of the most consistent fuel-assembly data compiled. The spread in the pressure loss data for all assemblies tested having the simulated grid piece attached to the inlet was less than the 2.6 percent at the maximum flow rate of about 500 gallons per minute. The presence of the simulated rod guide overhangs resulted in a 2.5-pound-per-square-inch increase in the overall pressure loss at 500 gallons per minute. These results suggested that perhaps the flow through those assemblies in the core that are situated between two control rods would be lower than that through assemblies with no overhanging guide. As mentioned in part I, the guides did not appear to influence the flow through the assemblies between rods. The static pressures measured inside the square hole of the grid indicated the presence of a flow separation due to the square corner at the leading edge of the hole. As the flow contracted from the 6-inch calming chamber into the square-edge grid hole, the main flow stream apparently separated from the hole wall such that the mainstream underwent an additional contraction inside the hole. The bellmouth entrance on the grid reduced the mainstream flow separation in the grid and, as a consequence, resulted in a lower overall pressure loss of 1 pound per square inch at 500 gallons per minute.

The velocity, static-pressure, and total-pressure distributions among the fuel-plate cooling channels of four different fuel assemblies are shown in figures II-4 and II-5. As noted in the figures, each data set was measured by different combinations of removable and built-in probes. It is noteworthy that, although the total-pressure distributions were fairly uniform, the velocities were not uniform because the static pressure was not constant from channel to channel. Hence, it is shown that both total- and static-pressure probes are needed to measure the flow velocity in the fuel passages with reasonable accuracy. In all the assemblies the velocities were usually highest in the centrally located channels and lowest in those adjacent to the inside of the end fuel plates. The spread in the velocity data was a maximum of about 14 percent, which was sufficiently uniform to satisfy design requirements. When these data are compared with those measured in the core (figs. I-11 and I-12), it is evident that the flow pattern at the upper grid inlet has some influence on the velocity distributions in the fuel-assembly channels. Hence, the laboratory test data on fuel assemblies do not represent exactly the situation in the reactor core; thus, detailed measurements in the core are necessary.

Figure II-4(a) illustrates the importance of the relation between the velocity indicated by the probes and the true average velocity in the channel (see also part I, p. 20). Because the difference between the true and indicated velocities is not negligible, the relation between these two velocities for particular probes should be determined to assure reasonable precision in the measured data.

The flow characteristics of the two fuel-shim-safety rods measured in the loop are given in figures II-6 and II-7. As with the fuel assemblies, no water flowed around the outside of the rod, and the handling-tool holes were sealed. The velocity, total-, and static-pressure distributions shown in figure II-7 are for the same bulk flow through the rod as measured in the modified core at 17,700 gallons per minute; although distributions were measured at other rates, they are not given here. The velocities are reasonably uniform except in those passages adjacent to the tie plate and the end plates, where the passages have a smaller spacing. Even though only one rod section was tested, it is reasonable to assume, based on fuel-assembly data, that other shim-rod fuel sections would display similar velocity distributions. The same can be said for the fuel-section pressure loss.

As pointed out in part I (p. 9), the fuel-section flow characteristics as measured in the laboratory held true when the rods were in the core because the long upstream cadmium section isolates the fuel section from the entrance flow conditions. Only the fuel-section pressure loss needed to be measured in the core to establish all the other flow properties using the laboratory test data. Thus, laboratory tests were very useful in the determination of flow characteristics that would have been very difficult to measure in the core, especially the velocity and static-pressure distributions.

The laboratory tests also proved invaluable in developing the instrumentation for use in the core flow tests. The total- and static-pressure probes were found to give a reasonably accurate indication of the average velocities inside the fuel cooling channels. As discussed in part I, the true velocities were measurable to within ±2.5 percent. The data reproducibility was checked by inserting the rakes, in successive runs, such that each channel had a different probe in it. This was accomplished by merely rotating the rake 180° about the shank axis. The response of the rakes to changes in flow rate was improved by avoiding long lengths of small-diameter tubing. Probes having a 0.050-inch outside diameter were led into lead lines of 0.090-inch-diameter tubes within 12 inches, which thus reduced the response time to several seconds. The largest cause of increased response time was the volumetric displacement of the manometer fluids. On pressure-difference gages, steady readings were available within 2 seconds after a change in flow. These results led to the instrumentation actually used for the core tests.

CONCLUSIONS

Experiments were set up to measure the flow characteristics of the dummy fuel assemblies and fuel-shim-safety rods and to develop the instrumentation for use in the core. The velocities were found to be higher in the central channels of an assembly than those inside the end fuel plates, with the maximum spread between the highest and lowest velocity approximately 14 percent (from 27 to 32 ft/sec) at design flow rates of 30 feet per second. The static pressures a short distance upstream of the channel exits were not usually uniform and in some instances varied as high as 2 pounds per square inch. Inside the fuel section of the shim-safety rod, the flows in the narrow channels adjacent to the end plates and the tie bar were about 15 percent lower than the maximum, and the more centrally situated channels were rather uniformily supplied.

The overall pressure losses through the assemblies agreed with the calculated values to within 2.5 percent. Adding the simulated control-rod guide overhangs to the simulated upper grid increased the overall pressure loss, whereas the bellmouth decreased it.

The fuel section of a shim rod was calibrated for its pressure loss against the bulk flow rate through it. This fuel section and its calibration curve were used to determine the rate through the rod in the core tests by measuring only the pressure loss. Knowing the bulk flow then permitted the determination of the flow rate in each cooling channel of the fuel section because these rates were known for a wide range of bulk flows.

The overall performance and accuracy of the total- and static-pressure probes in these tests led to their use in the core tests. Thus, these laboratory studies proved to be a valuable portion of the overall hydraulic test program because the knowledge and experience acquired resulted in a better core testing program than could have set up without the laboratory studies.

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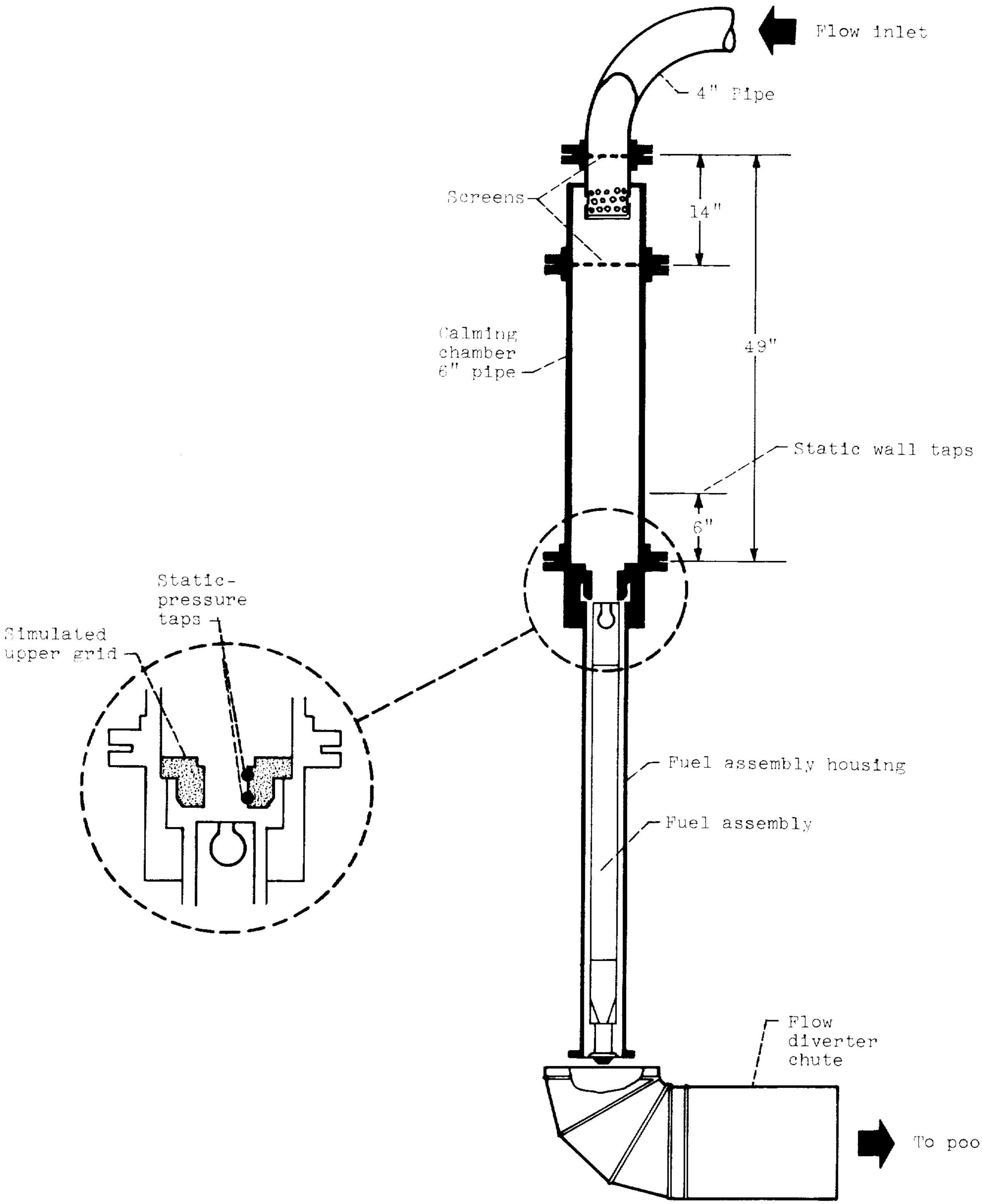


Figure II-1. - Laboratory test stand.

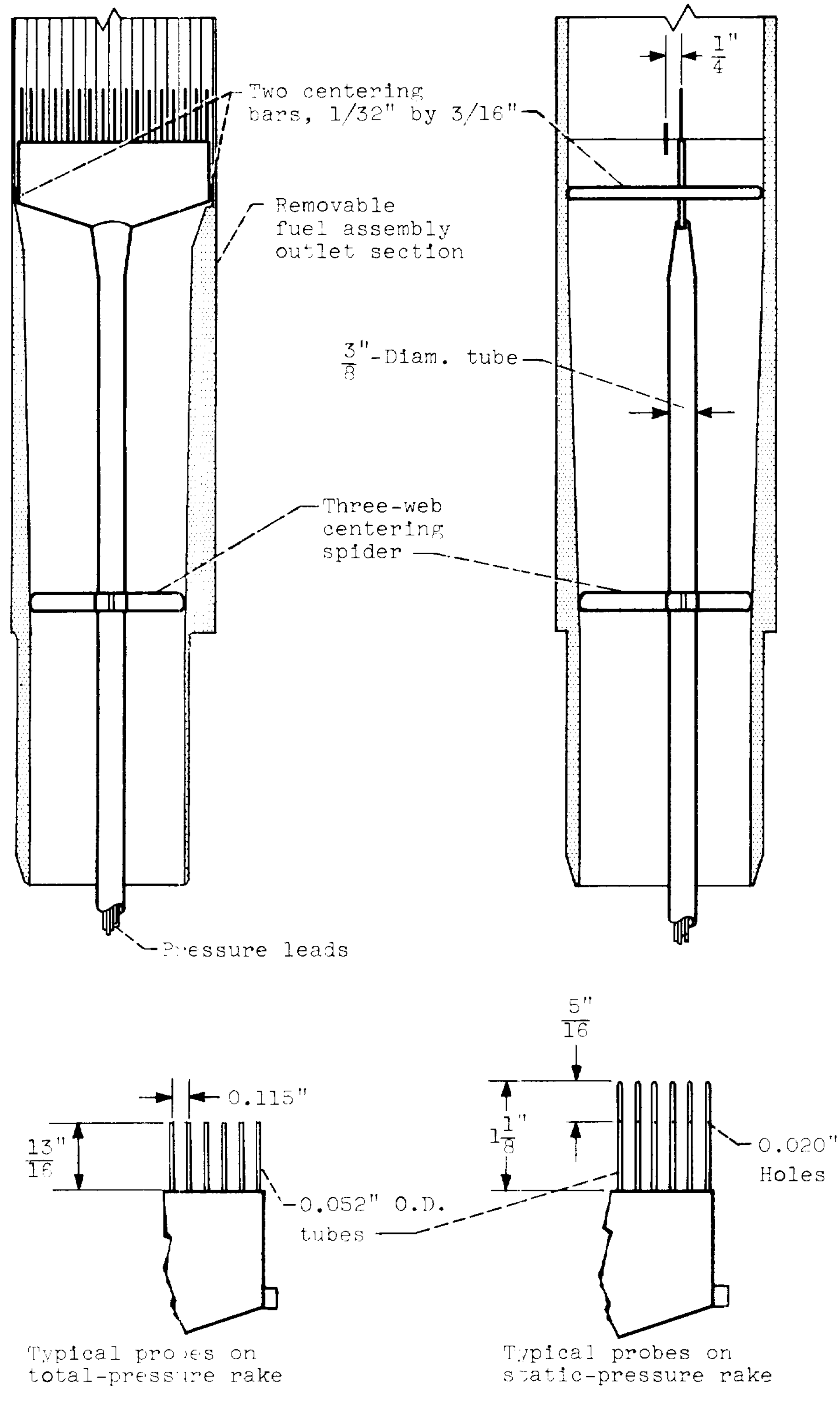


Figure II-2. - Details of removable total- and static-pressure rakes installed in position inside lower end box of fuel assemblies.

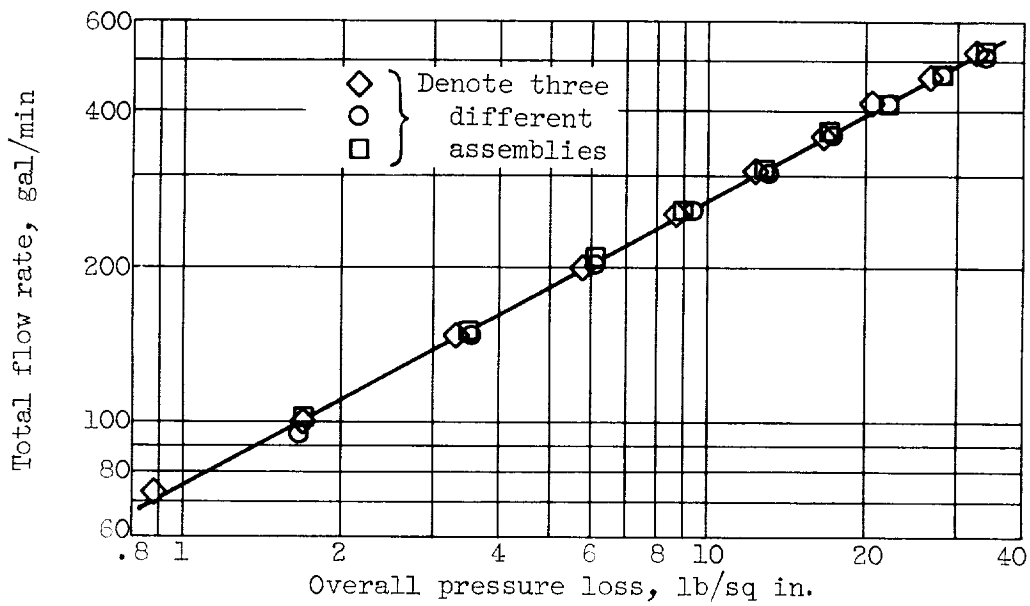
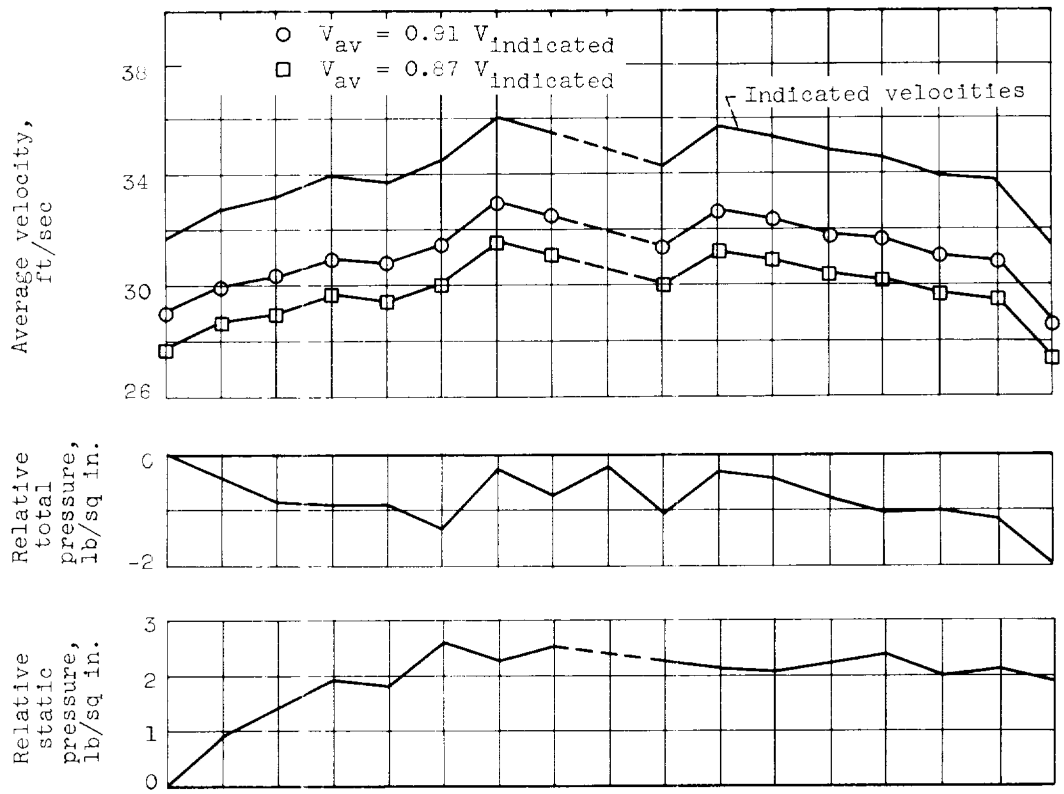
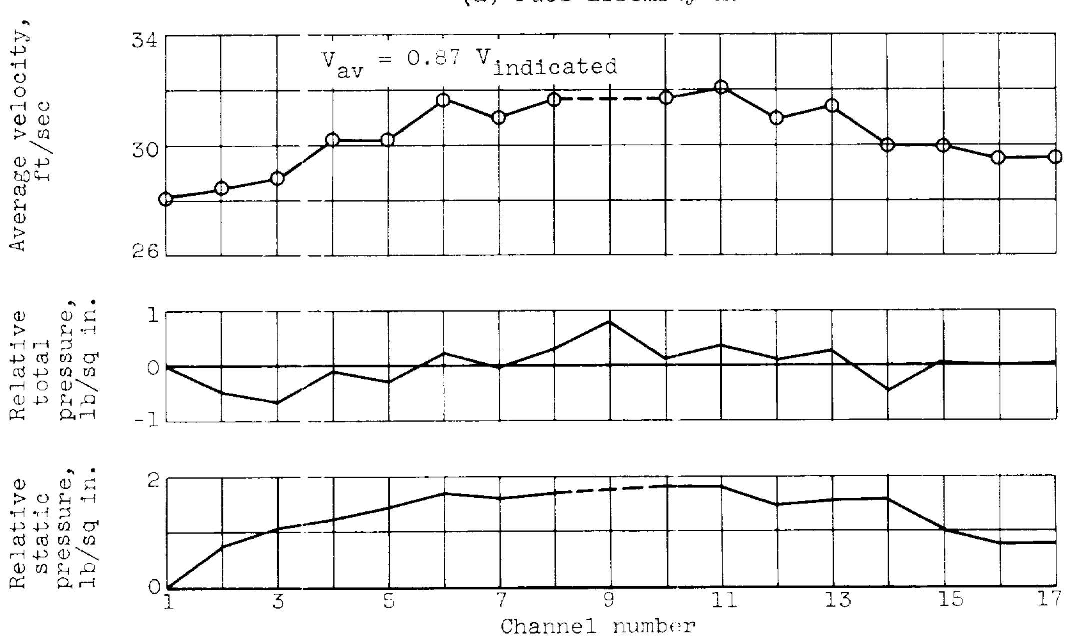


Figure II-3. - Flow rate against overall pressure loss characteristics for three dummy fuel assemblies as measured in laboratory test loop using the simulated upper grid inlet.

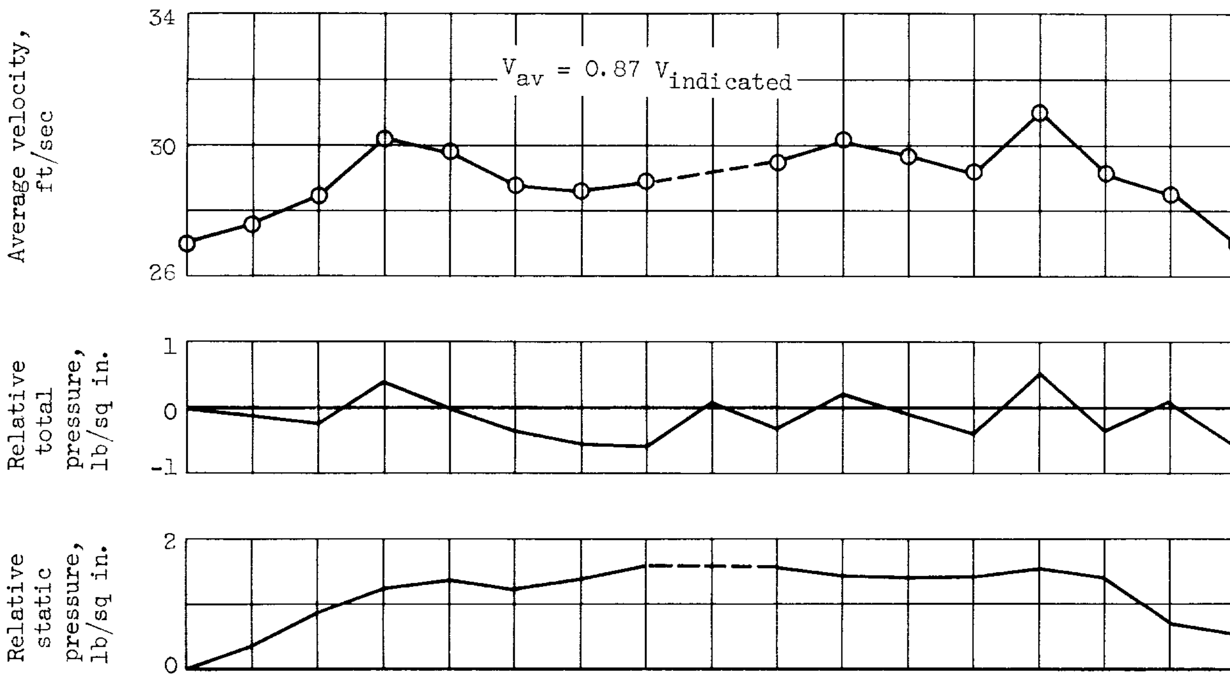


(a) Fuel assembly A.

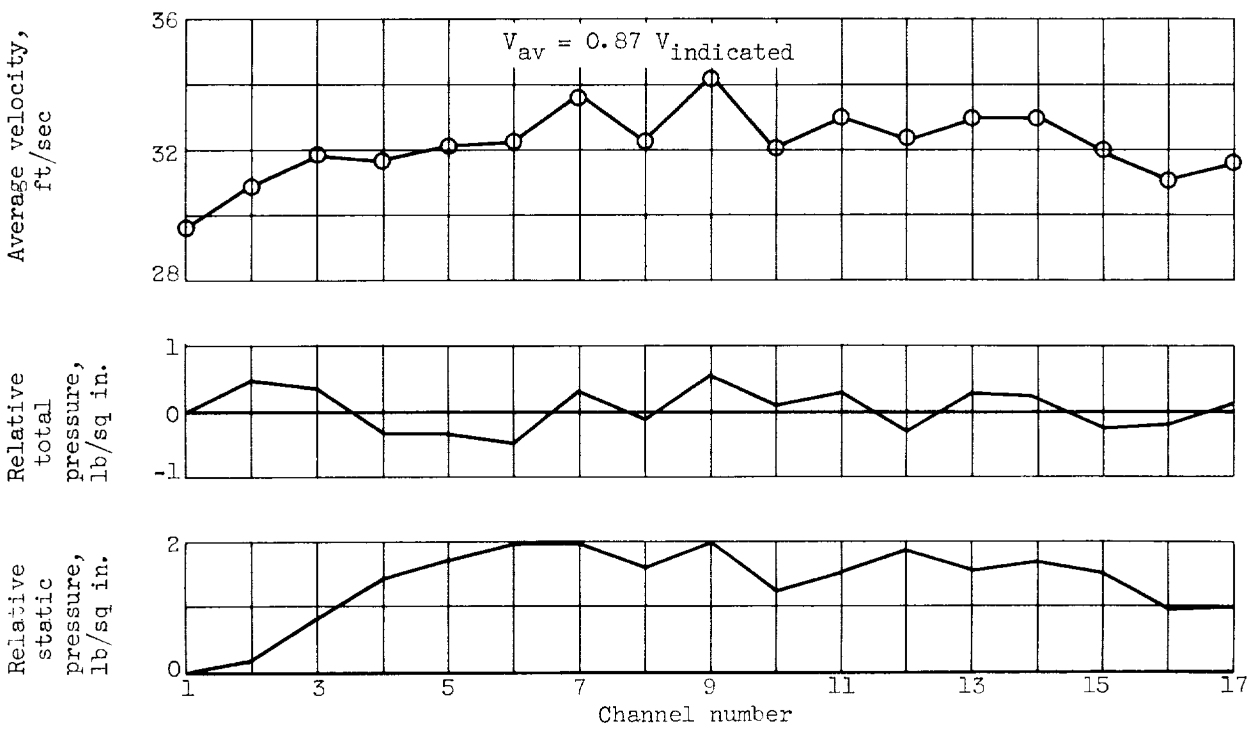


(b) Fuel assembly B.

Figure II-4. - Velocities and relative total and static pressures among cooling channels inside fuel assemblies A and B using builtin total-pressure probes and removable static rake. Total flow rate, 498 gallons per minute.



(a) Fuel assembly C.



(b) Fuel assembly D.

Figure II-5. - Velocities and relative total and static pressures among cooling channels inside fuel assemblies C and D using removable total- and static-pressure rakes. Total flow rate, 458 gallons per minute.

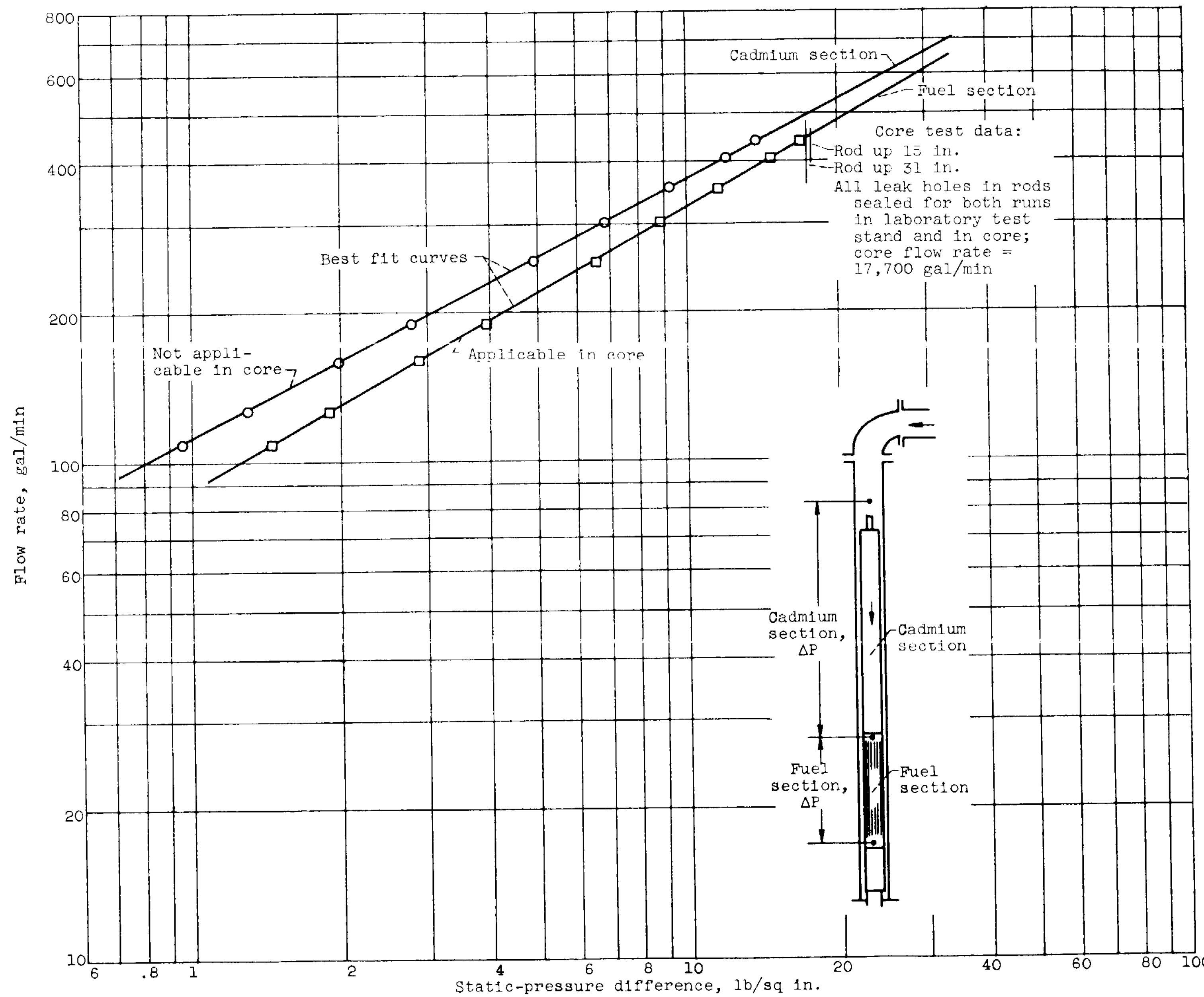


Figure II-6. - Static pressure against flow rate inside shim fuel rod measured in laboratory test stand.

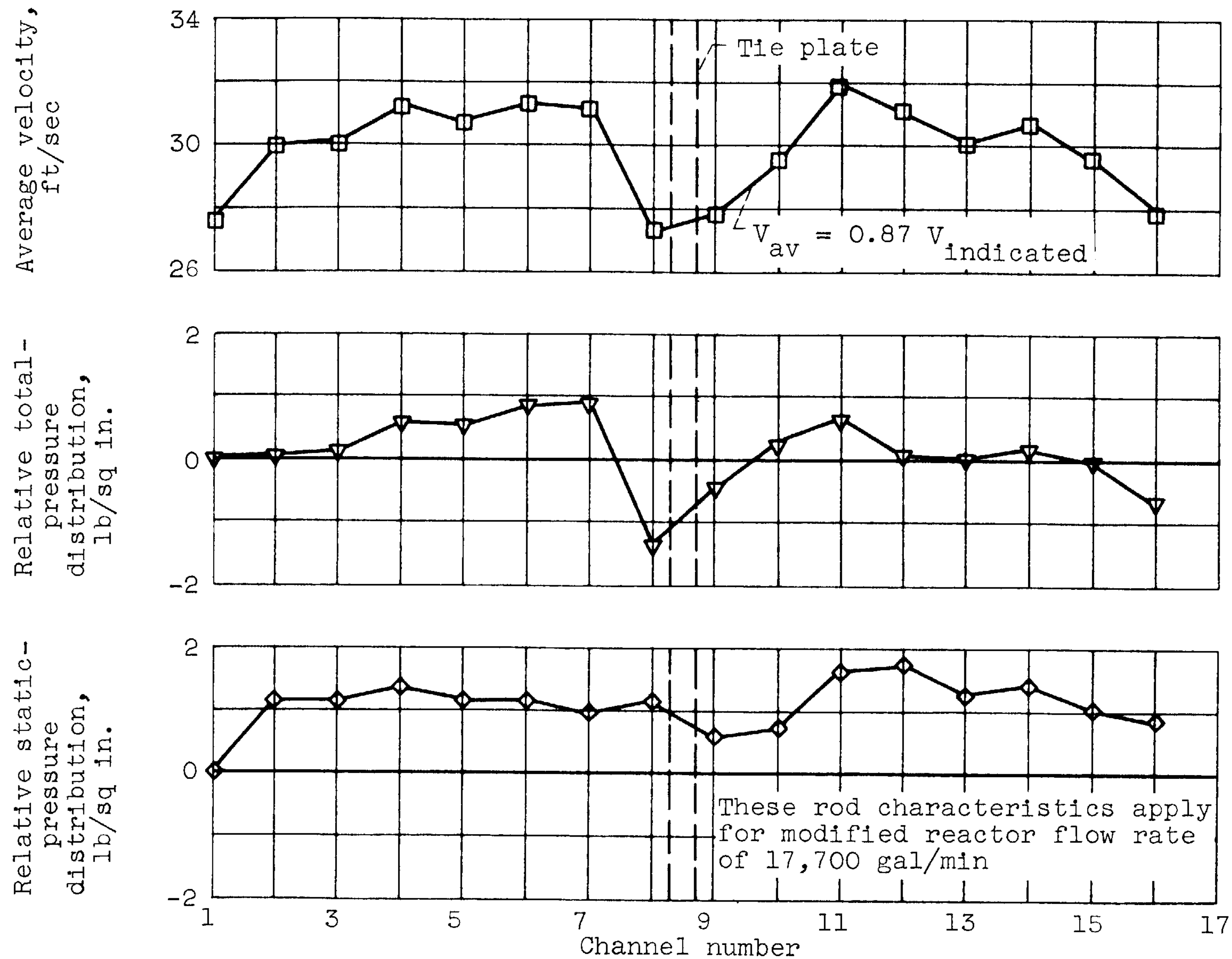


Figure II-7. - Velocity, relative total-, and static-pressure distribution among cooling channels inside shim rod fuel section as measured in laboratory test stand with removable probe rakes. Total flow rate, 449 gallons per minute.

III - AN INSTRUMENT FOR ACCURATELY MEASURING STEADY AND TRANSIENT BULK FLOW RATES THROUGH FUEL ASSEMBLIES IN THE CORE

SUMMARY

A pair of simulated fuel assemblies were developed specifically to measure the steady-state bulk flow distributions among the fuel-assembly positions of the core and the transient flow rates through the assemblies during the coast-down period after the main pumps were shut off. Each unit contained a turbine-type flowmeter and was designed to have the same overall pressure loss as the regular fuel assemblies. After the units were built, their pressure loss characteristics were checked and matched exactly to those of the dummy fuel assemblies in a laboratory flow loop (described in part II). Then the simulated assemblies were successfully used in the core tests (part I) where each assembly measured the true flow rate to within 1-percent accuracy. The flow distribution among the fueled regions of the core was uniform to within ±3 percent maximum deviation from the average rate of about 480 gallons per minute. These results agreed well with those measured by a dummy assembly containing velocity probes in each channel. Measurements of the flow rates during the coast down in the core showed that the flow rate coasted to 10 percent of the normal operating value in approximately 15 seconds after the primary pumps were shut off.

The performance of the simulated assemblies in the tests conducted in the laboratory and particularly in the core was excellent. Very little difficulty due to malfunctioning or breakage was encountered. Because these instruments proved to be so accurate and reliable, they can be, with appropriate modification, employed in other reactors.

INTRODUCTION

There are two flow characteristics of any nuclear reactor that are important to the proper cooling of the reactor: the flow distribution among the fuel assemblies in the core, and the transient flows inside the assemblies during the coast-down period after an accidental pump failure. During normal steady-state operations the flow distributions are necessary for calculating the heat-transfer characteristics and temperatures throughout the core. When a pump failure occurs, the reactor is shut down simultaneously to prevent it from overheating during the flow coast-down period because of the lack of proper cooling. Although the reactor is shut down, it continues to generate a sizable afterheat, caused by fission product decay, which decreases rapidly with time to a low value. If the flow coast-down rate is too rapid, the reactor can overheat and be damaged. For this reason it is very important to know accurately how rapidly the primary flow rate decreases after the pumps stop running.

A search through the unclassified literature revealed that several methods were used to measure steady-state flow distribution in reactor cores. On a quarter-scale model (ref. 1) of the PWR, the flow resistance of the fuel assemblies was simulated with orifice plates. Considerable difficulty was encountered in the application of the orifice plates before they were successfully used. On the PWR itself modified venturies and flow nozzles were mounted under each fuel assembly (ref. 2); however, no useful details were given regarding the design and operational experience. The flow distributions in the SPERT III core (ref. 3) were measured by a turbine meter that was mounted in series with a fuel assembly and also by a pitot tube inside the assembly. The disadvantage of this arrangement was that the flow resistance of the assembly was increased, which permitted only relative flow distribution measurement among the fuel-assembly positions of the core. Another difficulty was that in the SPERT III hydraulic tests the pitot tube measurements did not agree with those of the turbine meter. A study of these reports and many others shows that a satisfactory method for rapidly and accurately measuring the bulk flow distribution in the fuel region of the core has not been developed. Also, there seems to be no readily available information on techniques for making a reasonably precise determination of the important transient flow characteristics of the fuel assemblies. The purpose of part III is to provide a description of two identical simulated fuel assemblies that were very successfully used to measure the bulk flow-rate distribution and transient flow rates during the coast-down period of the fueled region of the PBR. Also included are an outline of the design method and the results of the laboratory and core tests.

DESCRIPTION OF APPARATUS

Several factors influenced the choice of the method for measuring the steady and transient flows through the fuel-assembly positions of the reactor core. One important requirement was that the instrument measure the same flow rate through a given position as flows through a typical fuel assembly in the same core location. This ruled out placing a flow-measuring device in series with a fuel assembly because the additional flow resistance would decrease the water rate through the assembly-meter combination. Hence, a simulated fuel assembly was conceived that would contain a meter and have the same overall flow resistance as a typical fuel assembly. Other requirements were that the flowmeter be capable of rapid response to changing flow rates for use in the transient flow measurements and have reasonably good accuracy. Also, the space limitation required that the meter be unaffected by short entrance and exit lengths. All these considerations led to the idea of placing a turbine flowmeter in a housing whose external shape was identical to the fuel assemblies (ref. 4).

The next problem was to incorporate the turbine meter in a fuel-assembly-like housing such that the overall pressure loss was the same as that of the actual fuel assemblies. A specially fabricated turbine meter was placed in the region normally occupied by the fuel plates, and the upper- and lower-end boxes were left unchanged. Hence, the design problem reduced to one of building a simulated fuel-plate region that contained the turbine flowmeter and whose pressure loss was identical to that fuel-plate array of a regular assembly.

The flow resistance of the turbine meter was much less than the friction loss of the rectangular channels, which necessitated that an additional flow resistance be placed in series with the meter. A cluster of parallel tubes was chosen in order to duplicate as nearly as possible some of the fluid friction pressure loss of the rectangular passages. The design calculations for matching the pressure loss of the meter-tube cluster combination to that of the fuel-plate section are presented in the appendix.

Two simulated fuel assemblies were constructed for use in the core flow tests. Figure III-1 is a photograph of the component parts of one of the assemblies, and figure III-2 illustrates the assembled general arrangement and installation in the core. Both figures are of the simulated assemblies prior to their modifications as a result of the laboratory tests. The turbine meter was of special design utilizing a signal pickup situated in the upstream bearing support. The pickup leads were encased first in a stainless-steel tubular sheath that extended upward out of the core for a short distance and then in a rubber tube sheath that extended out of the reactor tank. The braided wire cables supported the meter leads under tension to prevent whipping. The tube cluster was made of 90 tubes each having 0.220-inch inside diameter, 0.250-inch outside diameter and a 12-inch length, plus one 3/4-inch-inside-diameter center tube. Because the design calculations could not accurately take into account all the minor pressure losses, a vernier flow adjustment was provided, which later was removed, at the end of the large tube in the form of a variable flow area adjustment. Any minor mismatching of the overall pressure loss of the simulated assemblies with that of the typical dummy fuel assemblies was to be corrected by an appropriate change in the slot area.

The outputs of the turbine flowmeters were measured by pulse rate counters and strip-chart recorders; the latter were used primarily for the transient flow tests in the core.

The laboratory test loop in which the simulated assemblies were tested is described in part II.

TESTING PROCEDURES

In the laboratory tests the overall pressure loss against flow-rate characteristics were measured in the same manner as for the regular dummy fuel assemblies. The testing procedure is described in part II. Only the grid inlet configuration without the control-rod guides or the bellmouth was used in these tests. The flow rate was varied from 50 to 510 gallons per minute, and the water temperature remained fairly constant in the range from 65° to 70° F. The procedure used to install the simulated assemblies in the core and to prepare for a run is given in part I. One assembly was retained in the same core position, LC-5, for all tests in which the simulated assemblies were used. This assembly served as a standard against which the second assembly was compared. The second assembly was moved to a new position after each successive run until the steady flow rate was measured at each fuel-assembly position of the core. Most of the steady flow data was recorded at the design full-power rate of 15,500 gallons per minute for the unmodified core. Several measurements were made at shutdown rates of 1600 and 1164 gallons per minute, and a limited amount of data was taken at intermediate rates. The measurements of the transient flow rates during coast down were made at the end of a steady-state run at design rate for full power. The strip-chart recorders were turned on, and the power to the primary pumps was turned off.

RESULTS AND DISCUSSION

Laboratory Tests

These tests were primarily for matching the overall pressure loss against flow-rate characteristics of the simulated assemblies to those of the typical dummy fuel assemblies, particularly at the high flow rates. If after each test the pressure losses did not match, the setting of the flow-area adjusting nut was changed accordingly. Because the turbine meter pressure losses were higher than was anticipated in the design, the final changes called for modifications of the meters, removal of the adjusting nut, and an enlargement of the 3/4-inch central tube in the cluster. The results of the final tests are shown in figure III-3, where it is seen that the matching was very close (within 3 percent) at the high rates and quite satisfactory over the entire flow range.

The accuracy and reproducibility of the laboratory tests were very good. The overall pressure loss was always measurable within 1 percent at the very low flow rates. The venturi and turbine meters in the test loops were calibrated and always measured the flow within 1/2 percent of each other. The steadiness of the flow rates was indicated by the frequency output of the turbine meters, which seldom varied over ±1 cycle per second at a maximum rate of 200 cycles per second. Because of the flow steadiness and the accuracy of the instruments, the meters in the simulated assemblies and those in the test loop agreed to within 1/2 percent. Thus, the laboratory test indicated that the simulated assemblies could be confidently used in the core tests for all flow rates including the shutdown conditions.

Core Tests

The simulated assemblies were used only in tests on the unmodified core. The results of steady-state measurements are summarized in figure III-4, where the rate measured by the meter inside the simulated assemblies is plotted against the measured core pressure loss. The curves calculated (see part I, DATA PROCESSING) for typical assemblies in the core are included for comparison. The agreement between the measured data and the calculated curve is within 5 percent except for a few points, which were about 12 percent off. The flows of the simulated assemblies also agreed within 3 percent with those evaluated from the velocities measured in the individual fuel-plate cooling channels of the dummy assembly used in part I. The flow through the primary water system was very steady. Hence, the precision of the simulated assemblies allowed an accurate measurement of the flow distribution among the fuel-assembly positions of the core. As mentioned in part I, the rates at any position did not vary over ±3 percent from the average value of 480 gallons per minute.

The transient flow rates during the coast-down period after the pumps were turned off are shown in figures III-5 and III-6. The shutdown flow loops were not in operation during these tests. When the two primary pumps were turned off simultaneously, the flow coasted to 10 percent of fuel rate in approximately 15 seconds; whereas with one pump operating the time was about 13 seconds. (Turning the second pump off 11 sec after the first pump was turned off was essentially the same as the second pump running alone.)

As seen from the results, the overall performance of the simulated assemblies was quite satisfactory. The reproducibility of the data was very good. Little difficulty was encountered due to breakage during operation. In short, the instruments proved to be valuable to the success of the core tests.

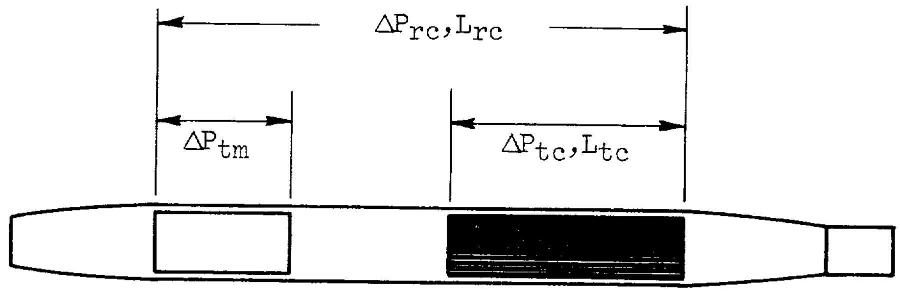
CONCLUSIONS

A pair of identical simulated fuel assemblies were developed and used to measure accurately two important flow characteristics of NASA Plum Brook Reactor: the steady-state flow rate through the inside of the fuel-assembly positions of the core, and the transient rates through them during the coast-down period after the main pumps were shut off. The units were identical to typical fuel assemblies except that the fuel plates were replaced with a turbine flowmeter in series with a cluster of tubes.

The overall pressure loss against flow-rate characteristics of the simulated assemblies were matched in a laboratory flow loop to those of a group of typical fuel assemblies whose data varied within a maximum error span of 3 percent over the range of 50 to 510 gallons per minute. When employed in the core tests, the two instruments measured steady flow distribution among the fuel-assembly regions of the core, and the distribution was uniform to within ±3 percent of the average. The transient measurements during the coast-down period showed that the flow rate in the unmodified core coasted to 10 percent of the value needed for fuel power operation in approximately 15 seconds. Because the two instruments proved to be accurate and dependable in the NASA reactor flow tests, it is believed that similar devices can be used in many other reactors.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, March 25, 1963

APPENDIX - DESIGN CALCULATION



To match the flow characteristics of the turbine meter - tube-cluster combination to those of the fuel-plate section of a regular assembly, the total flow rate and the overall pressure loss had to be the same for each. It was assumed that (see sketch)

$$\Delta P_{rc} = \Delta P_{tm} + \Delta P_{tc} \tag{A1}$$

where ΔP_{tm} is the overall pressure loss of the turbine meter, ΔP_{tc} is the tube-cluster pressure loss, and ΔP_{rc} is the frictional pressure loss of the array of parallel rectangular fuel cooling channels. All the other losses such as the inlet contraction and outlet expansion losses to the meter and the cluster were assumed to be approximately equal to those of the fuel-plate assembly. Also, the friction loss in the round passage between the meter and tube cluster was negligible. The friction pressure losses ΔP for smooth tubes and rectangular channels are represented by the relations

$$\Delta P = 2f \frac{L}{D} \rho V^2 \tag{A2}$$

$$f = \frac{0.046}{Re^{0.2}} \tag{A3}$$

$$Re = \frac{DV}{\nu} \tag{A4}$$

where

f friction factor

L channel length

D equivalent diameter

ρ fluid density

V average fluid velocity

Re Reynolds number

ν kinematic viscosity of fluid

The equivalent diameter for a rectangular channel is defined as

$$D_{rc} = 2\left(\frac{Wh}{W + h}\right) \tag{A5}$$

where W is the distance between the short walls and h is the spacing between the broad walls. Substitution of equations (A2), (A3), (A4), and (A5) into equation (A1) results in the following relation between the average velocities in a rectangular channel and a round tube:

$$\frac{V_{tc}}{V_{rc}} = \left[\left(1 - \frac{\Delta P_{tm}}{\Delta P_{rc}}\right)\left(\frac{L_{rc}}{L_{tc}}\right)\right]^{5/9}\left(\frac{D_{tc}}{D_{rc}}\right)^{2/3} \tag{A6}$$

where subscript tc is for round tubes and rc is for rectangular channels. Since the total flow through the tube cluster of the simulated fuel assembly was to be the same as for all the rectangular channels of a typical assembly, some number of tubes had to pass the same volume rate per channel; that is,

$$N\left(\frac{\pi D_{tc}^2}{4}\right)V_{tc} = (Wh)V_{rc} \tag{A7}$$

where N is the number of tubes per channel. Combining equations (A6) and (A7) results, after simplification, in

$$N = \frac{2^{8/3}}{\pi}\left[\left(1 - \frac{\Delta P_{tm}}{\Delta P_{rc}}\right)\left(\frac{L_{rc}}{L_{tc}}\right)\right]^{-5/9}\left(\frac{W}{D_{tc}}\right)\left(\frac{h}{D_{tc}}\right)^{5/3}\frac{1}{\left(1 + \frac{h}{W}\right)^{2/3}} \tag{A8}$$

Equation (A8) is general, and it permitted easy calculation of the number of tubes per channel required in the cluster for the most frequently expected operating conditions during the core tests. The h, W, L_{rc}, and ΔP_{rc} of a typical fuel-assembly-plate cooling channel were known. The ΔP_{tm} was supplied by the turbine-meter manufacturer. The turbine-meter length plus 2 or 3 meter diameters of free space downstream placed a maximum limit on L_{tc}. The tube inside diameter D_{tc} was chosen very nearly equal to D_{rc} to match closely the Reynolds number in the tubes with that in the fuel-plate cooling channels. For these conditions the total number of tubes (0.250-in. O.D. × 0.220-in. I.D. × 12 in. long) needed in the cluster was calculated to be 111. However, only 98 tubes could be assembled in the available space. As a compromise 90 tubes were combined with a 3/4-inch-inside-diameter tube that was hydraulically the equivalent of about 27 of the smaller tubes and thus represented a total of 117 tubes.

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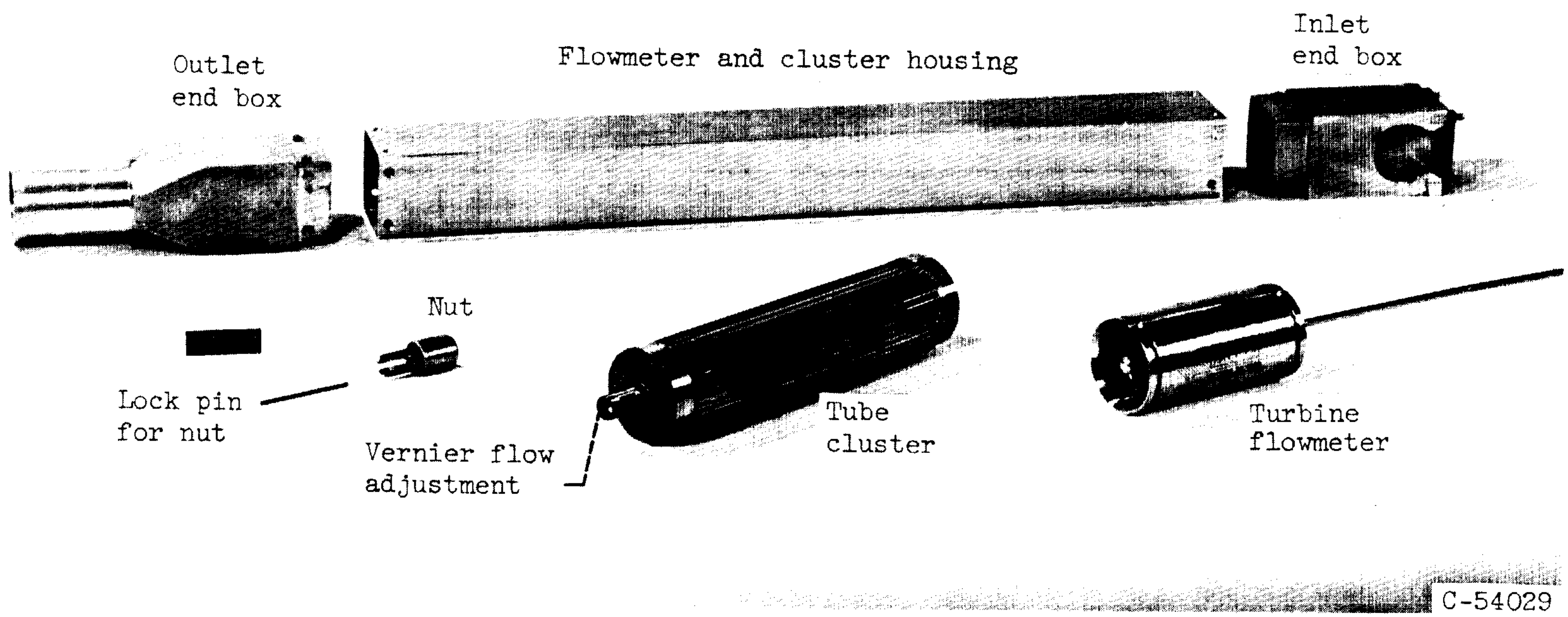

Figure III-1. - Components of simulated fuel assembly.

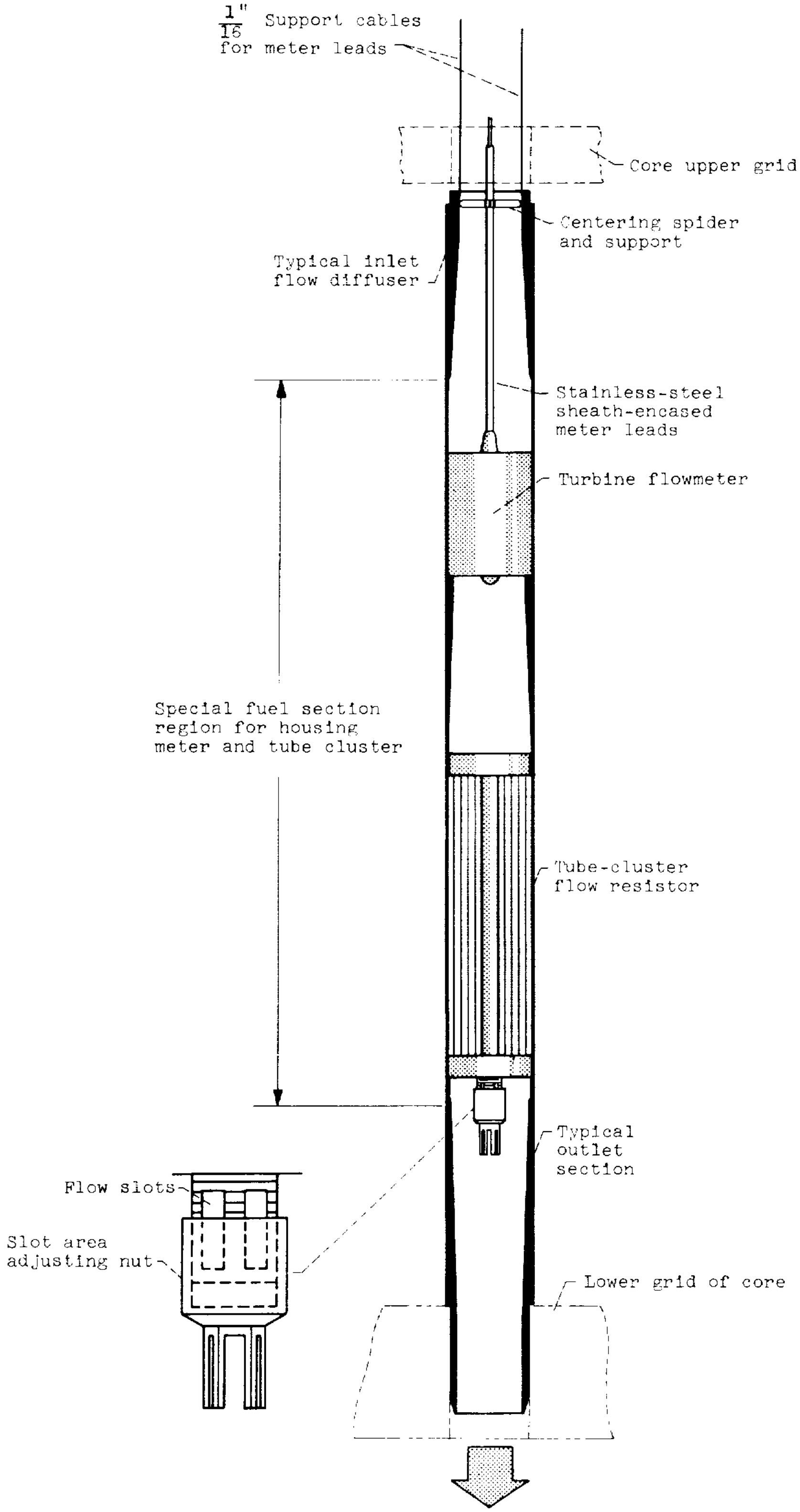

Figure III-2. - Schematic arrangement of simulated fuel assembly.

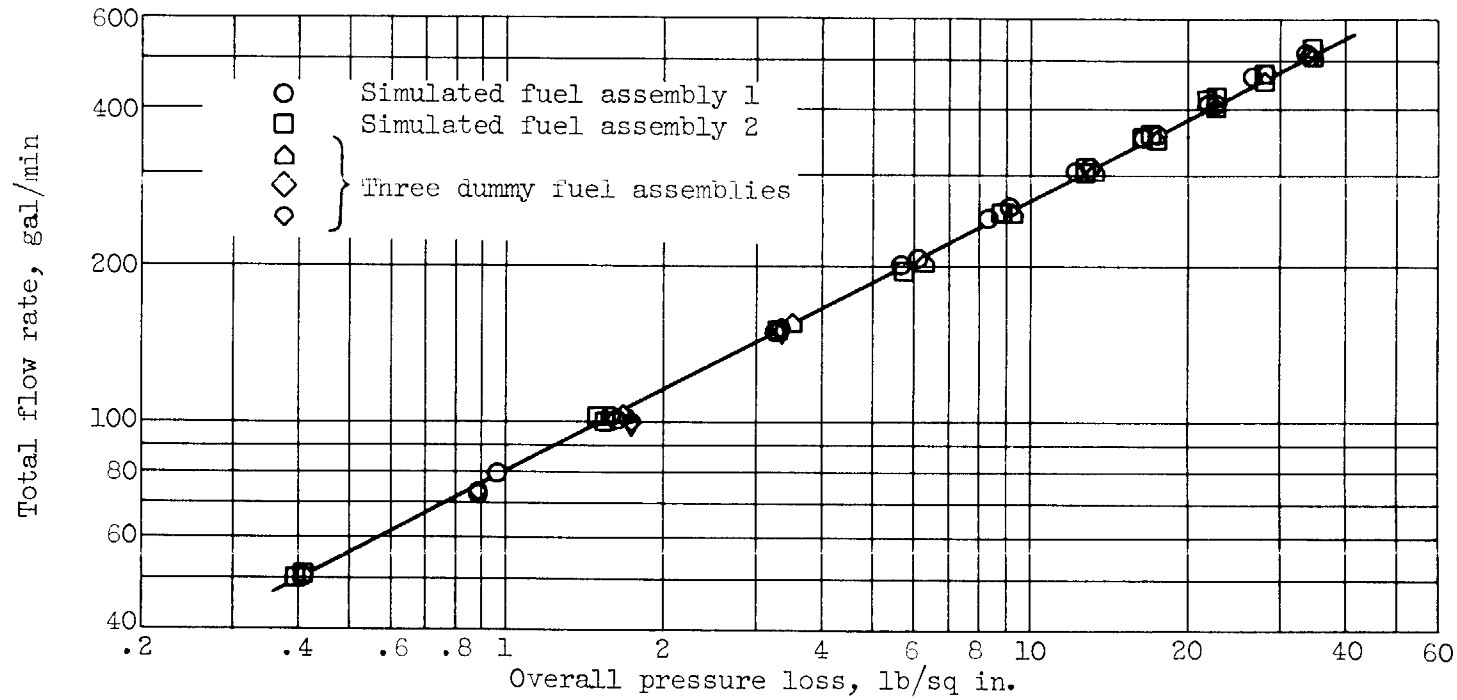

Figure III-3. - Comparison of bulk flow rate against overall pressure loss characteristics of two simulated fuel assemblies with three dummy fuel assemblies.

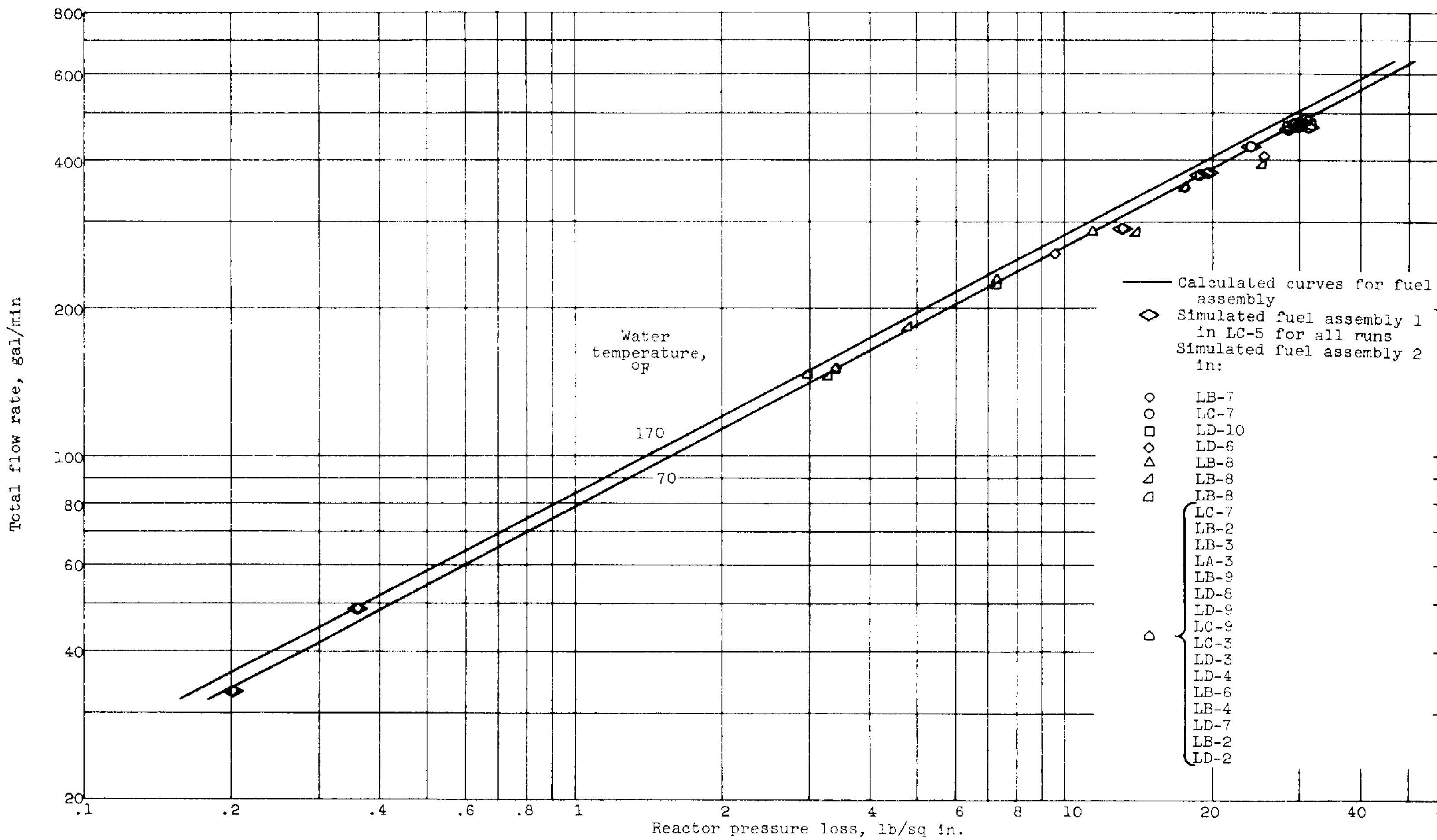

Figure III-4. - Total flow through simulated fuel assembly against pressure loss in various fuel-assembly positions of reactor core. Water temperature range, 65° to 93° F.

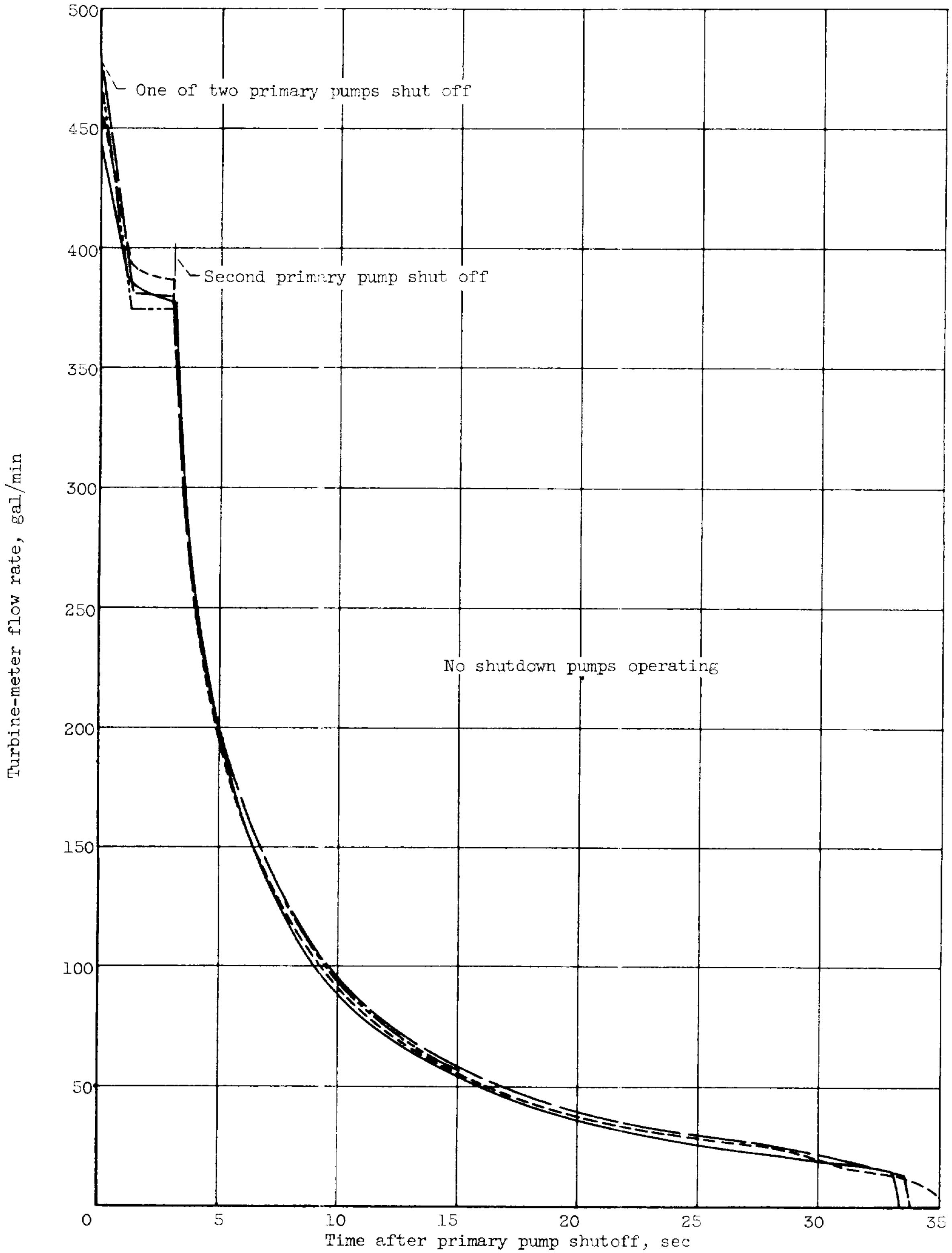

Figure III-5. - Transient flow rates through simulated fuel assemblies during coast-down after successive shutoff of pumps for four different tests.

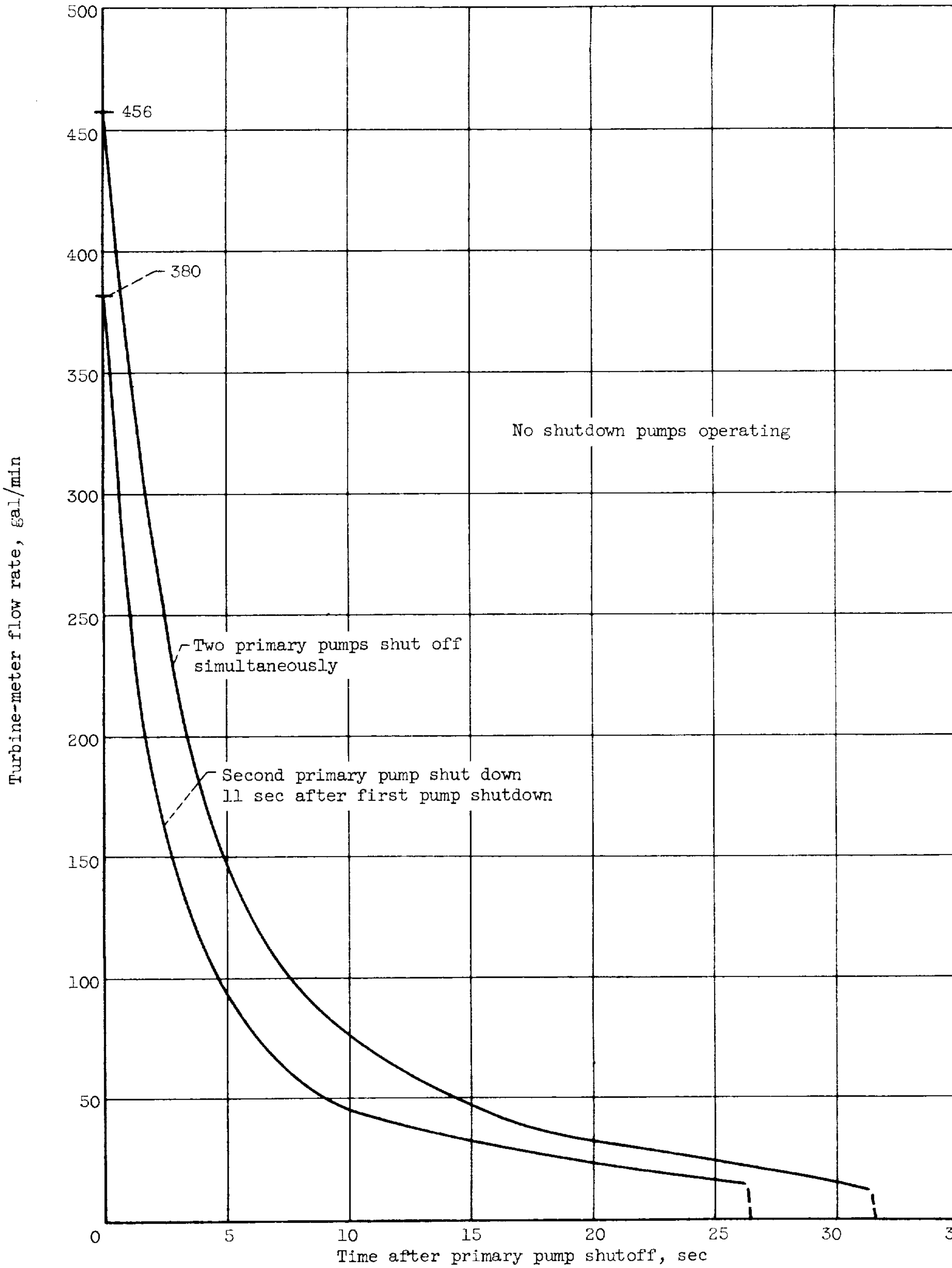

Figure III-6. - Transient flow rates through simulated fuel assemblies during coast-down.

NASA-Langley, 1963 E-1628